



**GDR**

**SCIPAC**

**SCIences of Particle ACcelerators**

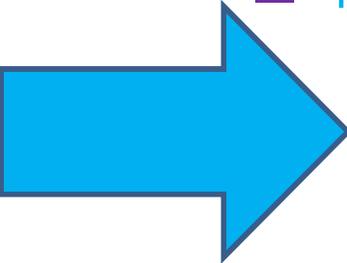
# Heavy Ion Accelerators in France

*B. Jacquot CNRS, GANIL*

GdR SCIPAC meeting

Genoble - march 2026

- Particle Accelerators ( $>1\text{MV}$ ) in the world ( $>10000$ )
  - Particle Accelerators in France ( $\sim 500$ )
    - Electron Accelerators in France ( $\sim 450$ )
    - Ion accelerators in France ( $\sim 60$ ) : only 10% of particle accelerators



-Medical Applications (radio-isotopes, treatments)  
-Research facilities

## Vast majority of the particle accelerators are for the medical applications

- 1) Radiotherapy (e-linac 5-20 MeV)
- 2) Radionuclides production with cyclotrons (10-30 MeV H<sup>-</sup>, H<sup>+</sup>, D)

**2 large research facilities** : light sources ESRF\_Grenoble ; Soleil\_Saclay

**Many smaller facilities** : irradiation X for many applications

**Radiotherapy (electron linac 6-25 MeV) : 400 linacs** 190 000 patients per year in France

Mobil X-Scanner for Truck inspection (drug, explosive...) : 4 in France (linac 6-1 MeV e)

Large X-scanner baggage in airport

Irradiation for industry : ATRON Cherbourg( 3.5 MeV/A),...

Irradiation for food : 1 facilities in France Troyes (10 MeV)

**Electron beams for research: > 10**

CERN CLEAR (eLinac- 220 MeV)

CLIO Orsay (50MeV e-linac, X-FEL), ALTO@ Orsay (50MeV e-linac)

THOM-X@Orsay(50MeV elinac +ring), Project PERLE@ Orsay

ELYSE @Orsay Accélérateur d'électrons picoseconde

LIONS lab@Saclay (ALIENOR : e LINAC 10 MEV // ACCIR : 60 keV egun )

ELSA@Bruyeres (e-linac 30MeV )

APOLLON @Saclay ( pulsed laser 10 PW, acceleration electron multi-GeV)

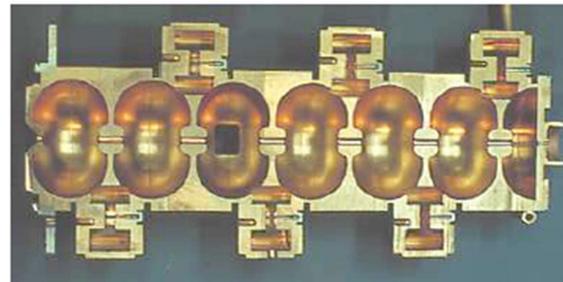
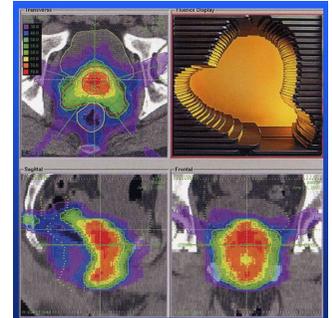
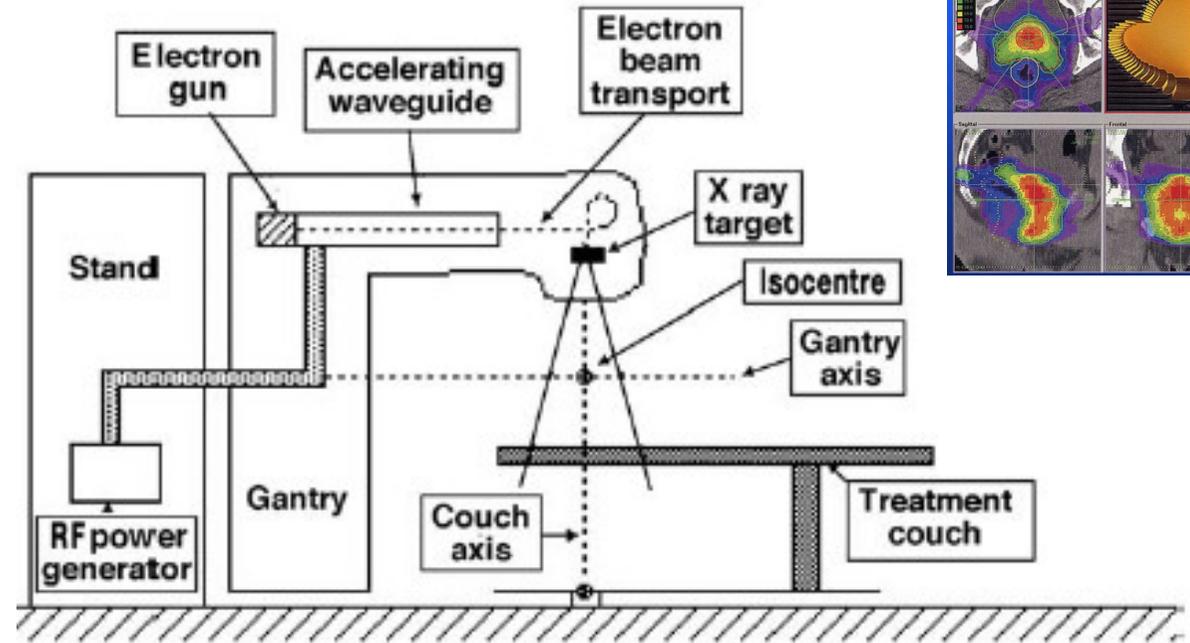
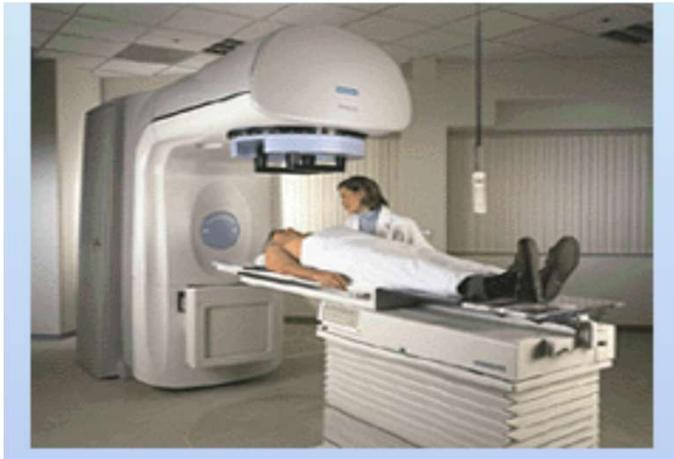
EPURE@CEA Valduc (3 e-linacs 20MeV )

Laboratoire des Solides Irradiés- Ecole Polytechnique (e 2.5 MeV)



## The most common accelerator (~ 400 in France)

A medical electron linac for radiotherapy : 5-20 MeV



Standing Wave (this picture)  
or Travelling Wave linac  
are possible

## Medical : isotopes production and treatment

Medical radio-isotopes (PET F18,...) : ~**30 cyclotrons** (10-18MeV)

Treatment: 2 synchro-cyclotrons (CAEN,NICE), 2 cyclotrons (ORSAY,NICE)

## Research : >25-30 (Nuclear Physics, Atomic physics, Material science, Medical)

CERN (>5 synchrotrons+3Linacs), GANIL@Caen (5 cyclotrons , 1 linac 40MV )

CYRCE@Strasbourg (cyclo K=25 MeV), ARRONAX@Nantes (Cyclo. K=70 MeV),

ARCHADE @Caen (Cyclotron K=1600 MeV en construction , S2C2 Proteus One K=230 MeV)

MOSAIC@Orsay (190kV, 2MV, 4MV), ALTO@orsay ( Tandem 14.5 MV)

SAFIR@PARIS-Jussieu (Van De Graaff 2.5 MV), NewAGLAE @Paris-Louvres(Tandem 2MV),

LEEL@Saclay (3.75 MV), ECHOMICADAS MHSN@ L'Orme (200kV)

ARTEMIS LMC\_14@Saclay (Tandem 3MV), DAM@Bruyeres (Tandem 7MV et VDG 4 MV)

ANAFIRE @Lyon (Tandem Van De Graaff 3.5 MV), GENESIS Grenoble (200 kV electrostatic)

ASTER @Aix en Provence (Tandem 5 MV), AMANDE@Cadarache (H- D-Tandem 2MV)

AIFIRA@Bordeaux (VDG 3.5MV ions Legers), CyCeron@Caen (cyclo K=18 MeV)

IPHI@ Saclay (H+ RFQ 3MeV=> neutrons)

M >4 amu

# 60 Ion Accelerators in France

## Acceleration Technology in France

<b>70% cyclotrons</b>	:	<b>40 (Cyclotrons+SynchroCyclo)</b>
		2 Linac
20% electrostatic	:	7 Tandems Van De Graaff
		3 Van De Graaff
		2 Electrostatic ~ 200kV

## Topics, Science

**Warning:** Accelerators have different applications (ex: GANIL=nuclear+commercial+radiobio.+...) + material science+...

65% : **32 for radionucleides production**

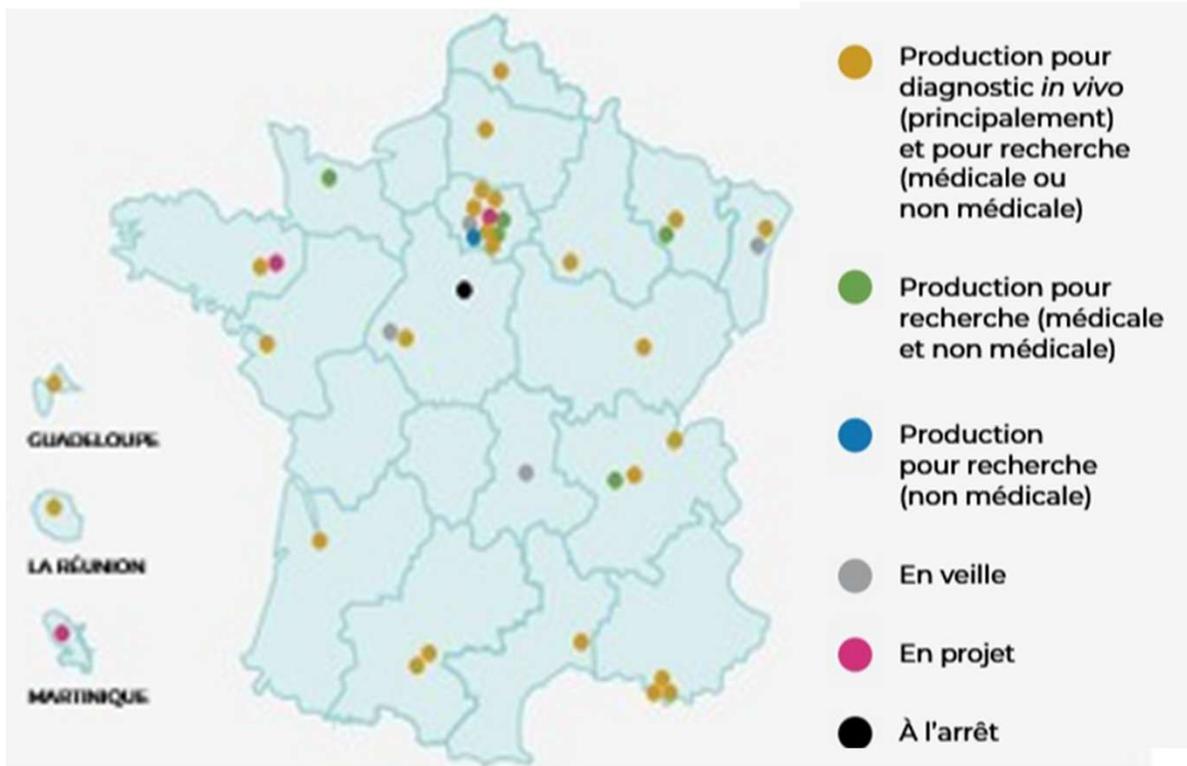
10% : **6 for Radiobiology, Medical research**

- : 10 Nuclear physics Research
- : 4 Environment, datation
- : 10 Material Science
- : > 5 Defense
- : **> 10 commercial irradiations**



**beam time**  
**~75% MEDICINE**

# Cyclotrons for medical radionuclides

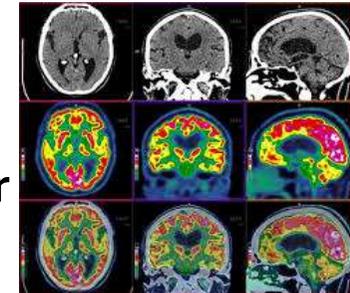


\* Info from: rapport ASN2023

## 30 cyclotrons (10-18MeV) for medical radionuclides production

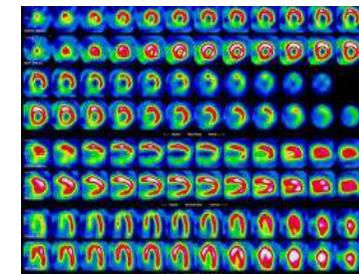
TEP Camera :  
fluor  $F^{18}$ , carbon  $C^{11}$ ,  $O^{15}$

Brain tumor



Scintigraphy :  
thallium 201, iode 123, gallium 67)

myocard



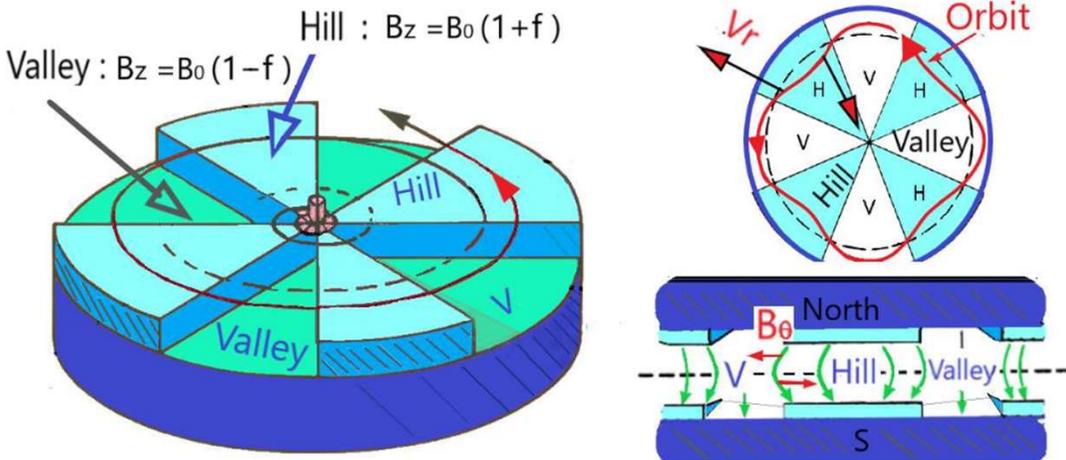
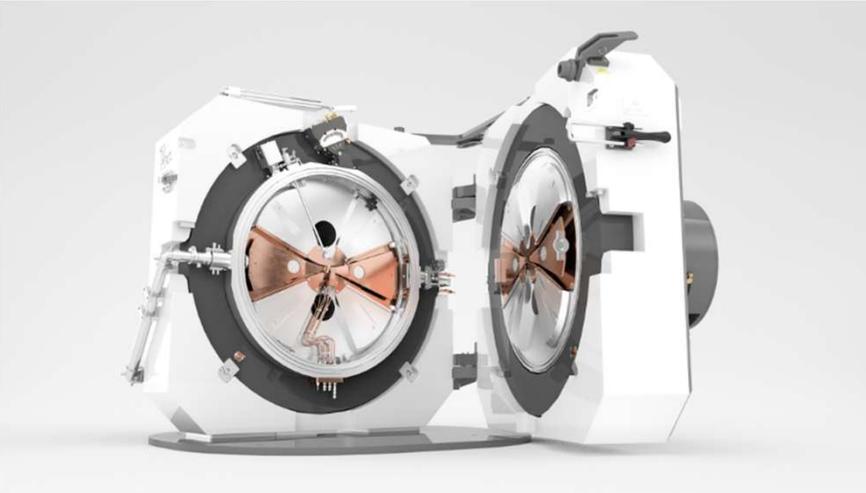
## 2 cyclotrons for research

+ ARRONAX 70 MeV protons  
+ CYRCE 25 MeV

CEMHTI Orléans cyclotron closed

# Medical cyclotrons in France

- Cyclotron technology :
- 1) isochronous acceleration  $F_{revolution} = \text{Constant} = F_{rf}/H$
  - 2) Azimutally varying field for vertical focusing (sectors)



$B_z = F(\theta) \Rightarrow$  azimuthal field component

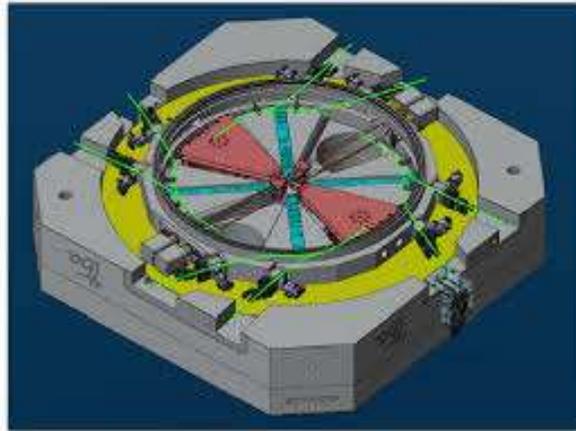
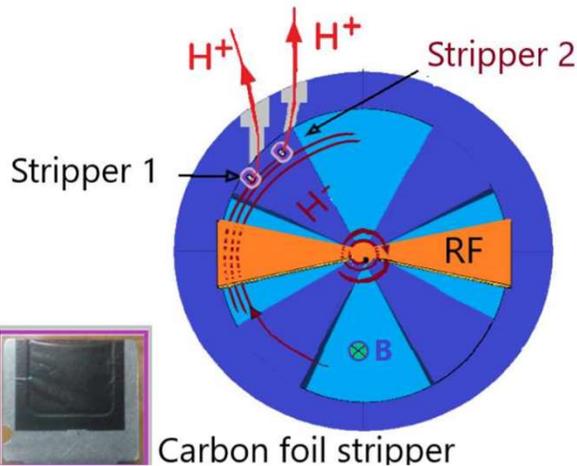
$$B_\theta = z \cdot \frac{dB_z}{Rd\theta} + \dots$$

Focusing force  $F_z^{AVF} = q(-v_r \cdot B_\theta) \sim -z$   
 Better transmission



# Medical cyclotrons in France

## Cyclotron technicology : 3) internal Negative ion source + the stripping extraction



H<sup>-</sup> = Easy extraction  
(no High Voltage deflector : fragil)

Several simultaneaous beams are possible (parallel operation)

*K factor for cyclotrons*

$$E_K/A = K_b \cdot \left(\frac{Q}{A}\right)^2$$

Ex : Cyclo K=10MeV => 10 MeV H<sup>+</sup>  
=> 2.5 MeV/A D<sup>+</sup>



## A common machine (# 10 items in France) : The Van De Graaff

A moving belt (nowaday pelletron)

Charge accumulation

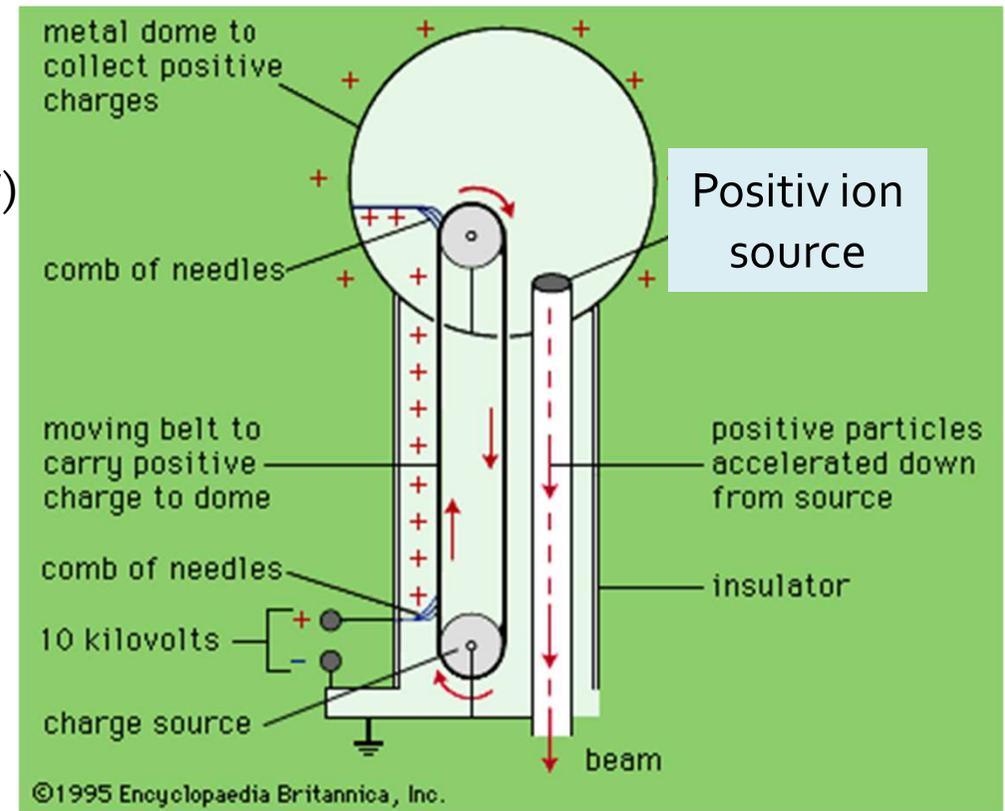
Static electric field

Ion source at high voltage on the terminal (1-10 MV)

IJCLAB/ Andromede (4MV Van de Graff)



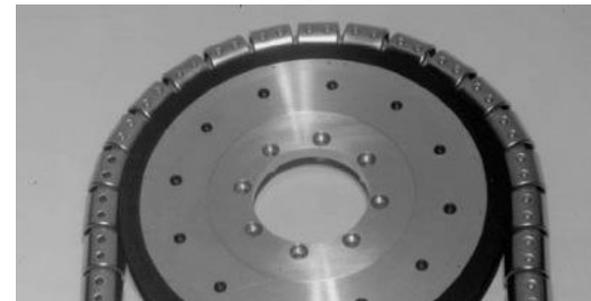
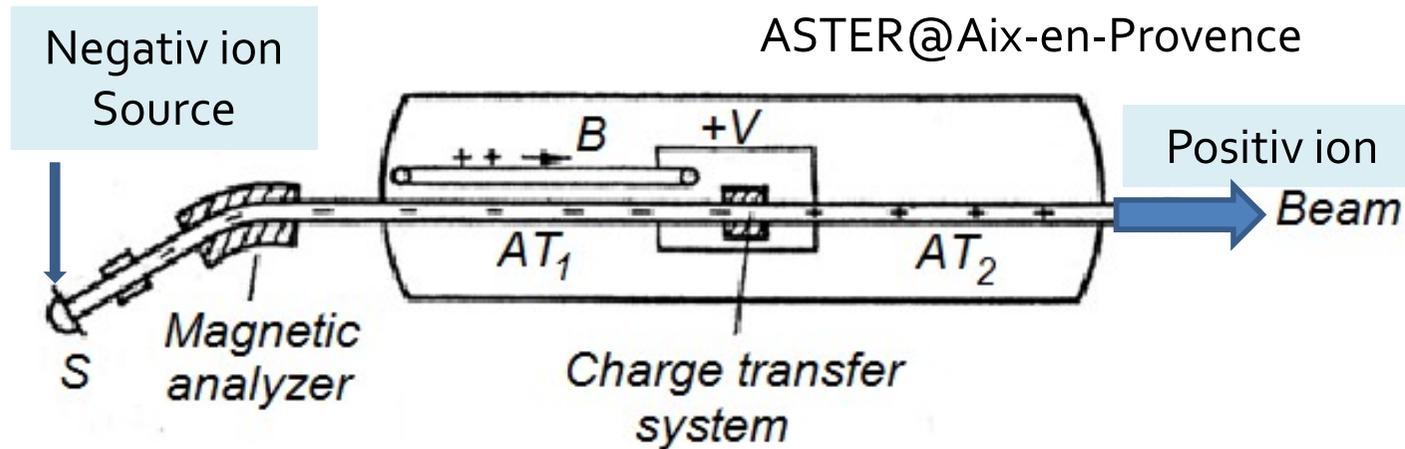
AIFIRA@Bordeaux



## The Tandem Van De Graaff : Two accelerations with 1 terminal

Ion Negative source

moving belt ( laddertron or pelletron) : attracting positive terminal  
stripping negative ( $H^-$ , ...) to positive ion ( $H^+$ )



Charge transfer  
Pelletron  
moving belt

IJCLAB/ALTO (Tandem 14.5 MV)  
H (25MeV) => Au (1.2 MeV/u) : # 30 Beams

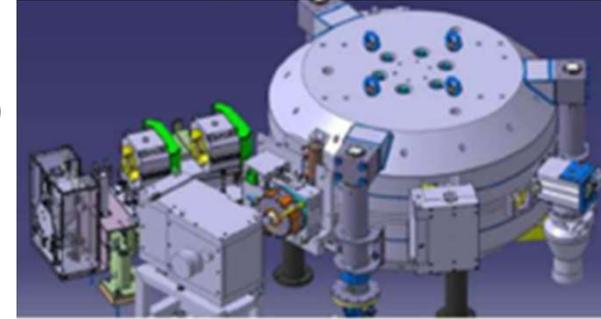
# Cyclotrons with Larger energies for treatment or research

## Treatment :

«S2C2 Proteus One » ARCHADE @ CAEN(SynchroCyclotron K=230 MeV)

LACASSAGNE @ NICE (SynchroCyclotron K=230 MeV)

very compact machine , sc 5 Tesla, H+ synchrocyclotron, Pulsed beam



CPO@ ORSAY (Cyclotron K=230 MeV)

LACASSAGNE @ NICE (Cyclotron K=65 MeV)

No Heavy Ion Synchrotrons(C,Ne) in France , but 4 in Europe 400 MeV/A

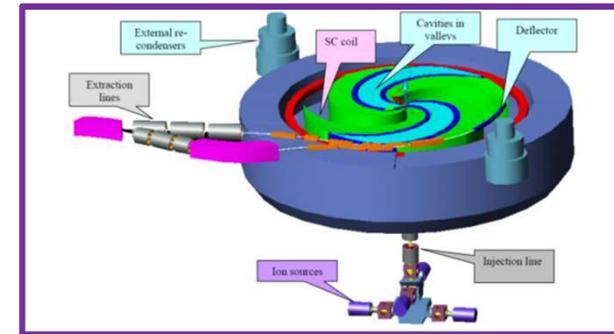
A big project : IBA C400 ARCHADE@ CAEN (Cyclotron for Carbon K=1600 MeV)

Hadron therapy with a very compact machine

## Research radio-isotopes

ARRONAX@Nantes (Cyclotron K=70 MeV)

CYRCE@Strasbourg (Cyclotron K=25 MeV)



# New Ion Accelerator for medical applications

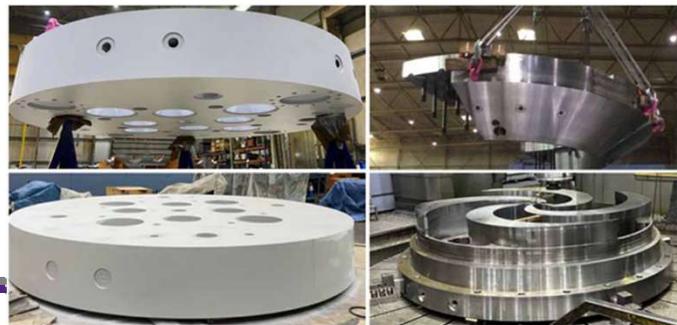
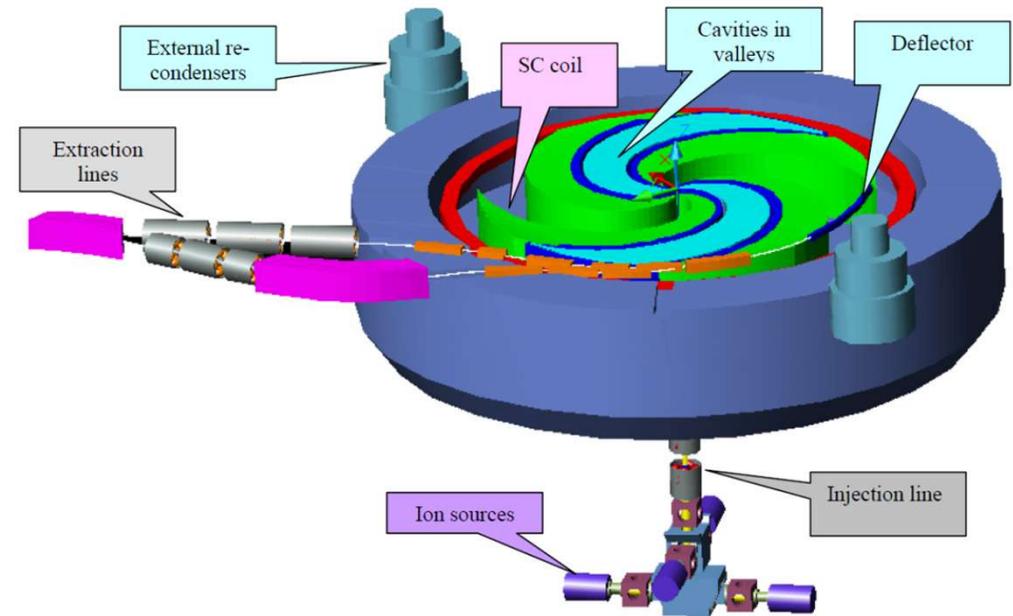
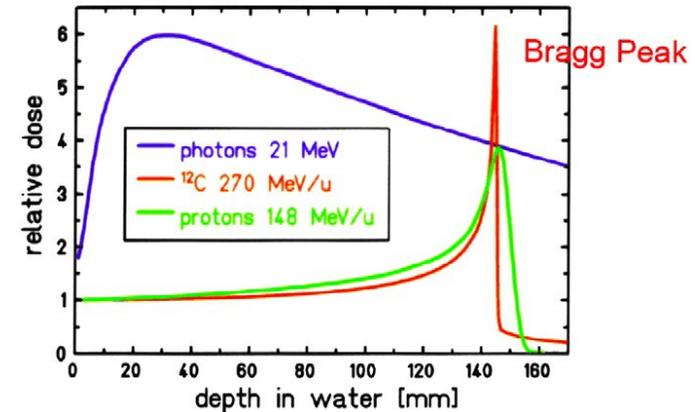
C400\_IBA : 400MeV/A  $^{12}\text{C}^{6+}$  / 260 MeV Proton  
Hadron therapy with a very compact machine

## Isochronous cyclotron K=1600 MeV; 660 tons

Diameter total 6.9 m; Rextraction: 1.8m  
Bfield 4,5 T (Hill) // 2.5 T (Valleys)  
RF =75 MHz; Harmonic  $H = F_{RF} / F_{revol.} = 4$   
Transmission ~ 0.5%,  
Beams :  $^{12}\text{C}^{6+}$ ,  $4\text{He}^{2+}$ ,  $\text{H}_2^+$  (260 MeV),

2024-25 :

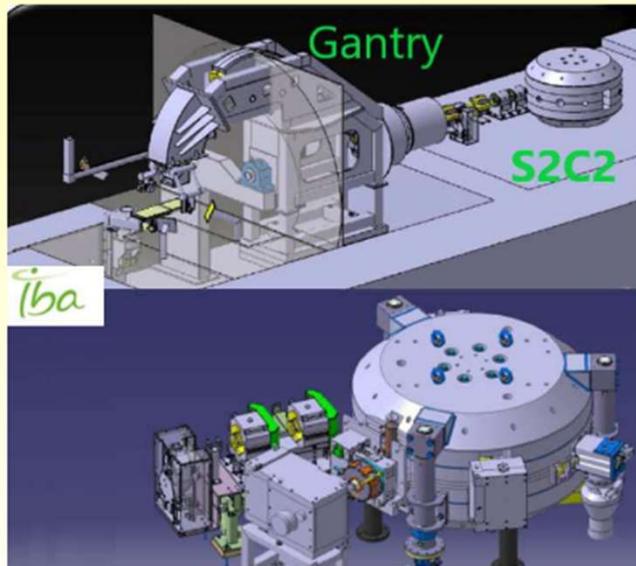
First model C400 being installed in **France**  
(Caen , Normandy, 2026 first cooling)



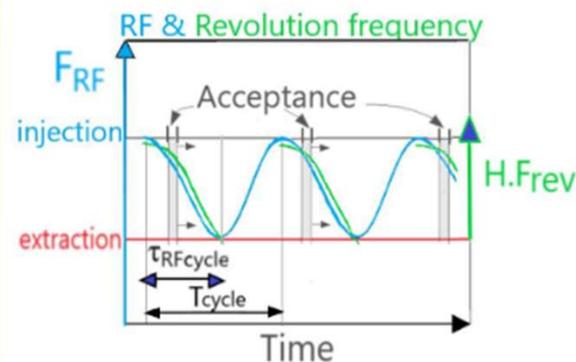
March 2026

# New H.I. Accelerator for medical applications

**SYNCHRO CYCLOTRON S2C2 (IBA)** the most compact accelerator for Proton cancer therapy at 230 MeV



$$\frac{qB_0}{m\gamma(R)} = f(\text{time}) = \omega_{rf}(t)/H$$



Very compact 5T superconducting magnet (No AVF: no sectors)  
 Radius= 49 cm  
 40000 turns  
 duty cycle=0.7% . FRF=[93 Mhz , 63 Mhz] (cycled) . Vrf= 10kV  
 Already 30 S2C2s constructed by IBA for cancer therapy centre in 2022  
 0.7% duty cycle



IBA synchrocyclotron@ 230 MeV  
 proton  
 (not isochronous cyclotron)

During the acceleration ,  
 revolution frequency is changing

RF is cycled to follow the proton  
 revolution frequency during  
 acceleration

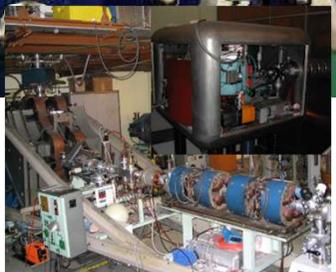
Beam is pulsed (low average  
 intensity) But very compact...

10 in construction for Spain  
 2 working in France (NICE, CAEN)

# Heavy Ion Accelerators in France



ALTO@IJCLab



Genesis@LPSC



CYRCES@Strasbourg



Research platform  
**mosaic**  
IJCLab



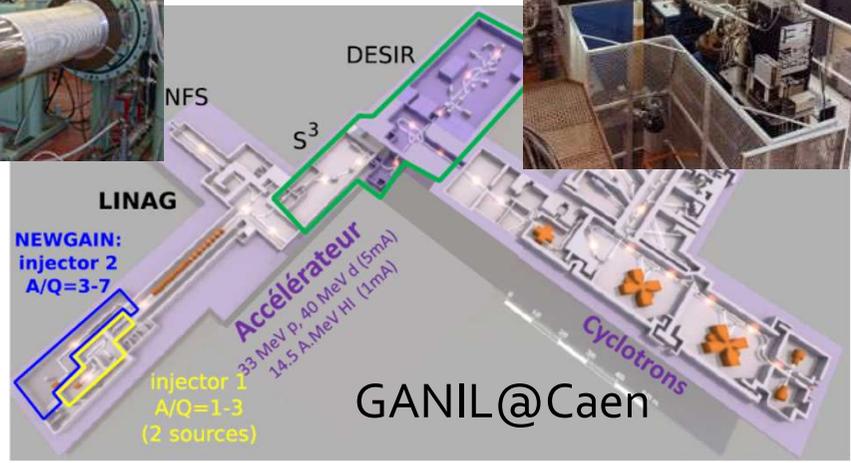
ARTEMIS@Saclay



SAFIR



7MV DAM



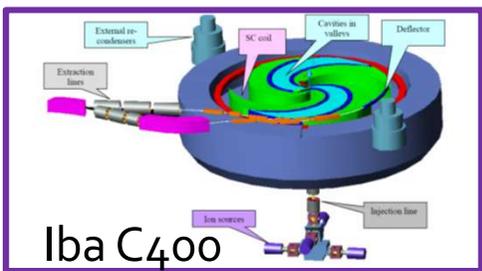
GANIL@Caen



ARRONAX



New AGLAE



Iba C400

# Applications of Ion Accelerators in France

## Radio-isotopes production

~30 cyclotrons in France (10-18 MeV proton, H-)

## Particle Physics

CERN (Protons+Heavy ions+neutrons)

## Material analysis (RBS,ERDA,PIXE,...)

Mosaic@orsay (190kV, Tandem 2MV, VDG 4MV)

Labo d'études des éléments légers LEEL@Saclay (3.75 MV)

AIFIRA@Bordeaux(VDG 3.5MV Light ions)

New AGLAE@Paris-Louvres (Tandem 2MV)

SAFIR@JussieuPARIS(Van De Graaf 2.5MV)

ANAFIRE @Lyon (Tandem Van De Graaff 3.5 MV)

## Environment, Datation (AMS, <sup>12,14</sup>C,...)

ASTER @Aix-en-Provence (Tandem 5 MV)

ARTEMIS LMC\_14@Saclay (Tandem 3MV)

ECHOMICADAS MHSN@L'orme

## Cancer Treatment with protons:

NICE (x2) , CPO, ARCHADE@Caen (x2)

## ~Nuclear physics

GANIL@Caen (5 cyclo.+ 1 Linac)

ALTO @Orsay (Tandem 14.5 MV)

DAM@ Bruyeres (4MV+ Tandem 7MV)

GENESIS@Grenoble (200 kV)

AMANDE CadaracheASNR (Tandem 2MV)

CERN Isolde (LINAC4+PSB+LINAC Isolde)

## Medical research, Radiobiology, Isotope research

ARRONAX

CYRCE

CERN (ISOLDE) MEDICIS



## Industrial applications, Commercial irradiations

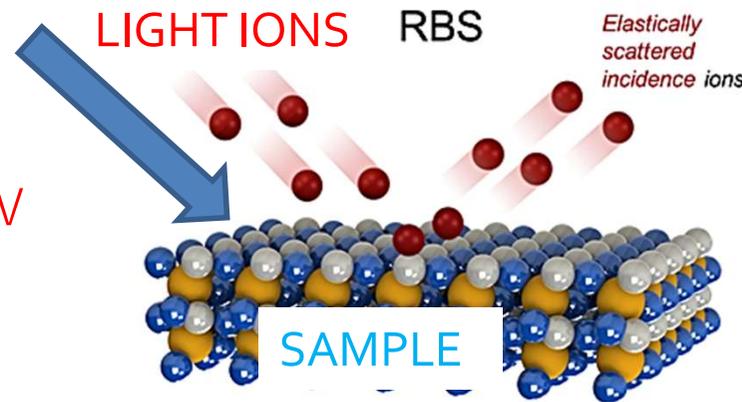
Electronic testing, Space application,...

# Ion beam Analysis with Accelerators

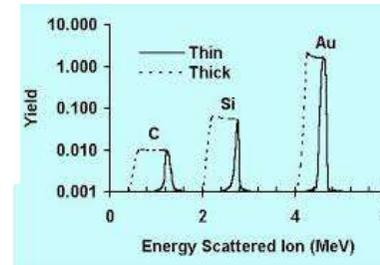
## Material analysis (RBS, ERDA, PIXE, ...)

MOSAIC@Orsay (190kV, 2MV, 4MV) // LEEL@Saclay (3.75 MV) // New AGLAE@Paris (Tandem 2MV)  
 ANAFIRE @Lyon (Tandem 3.5 MV)//AIFIRA@Bordeaux (3.5MV ions Legers)//SAFIR (2MV)

### Rutherford Back Scattering (RBS) with H,D,He 1-3 MeV

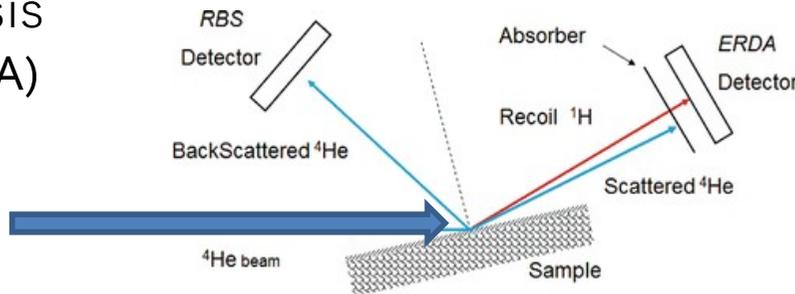


Quantitative analysis for RBS  
 Kinematic Factor ( $M_{projectile}, M$ )  
 Cross section ( $M_{projectile}, M, \theta$ )  
 Energy losses (depth,  $Z_{projectile}$ )

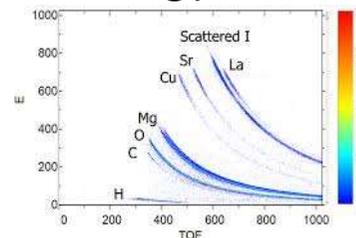


Not good for  
 light  
 elements

### Elastic Recoil Detection Analysis (ERDA)



### Energy Tof



### Quantitative analysis ERDA

Low scattering angle  $\theta$   
 good for light elements  
 Complementarity with RBS, PIXE

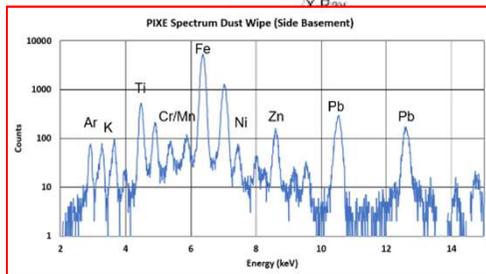
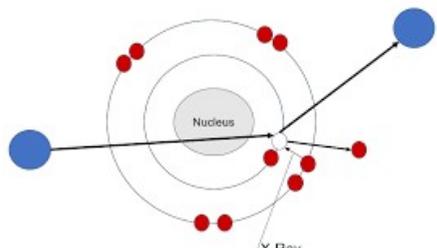
# Ion beam Analysis with Accelerators

## Material analysis (...,PIXE,...)

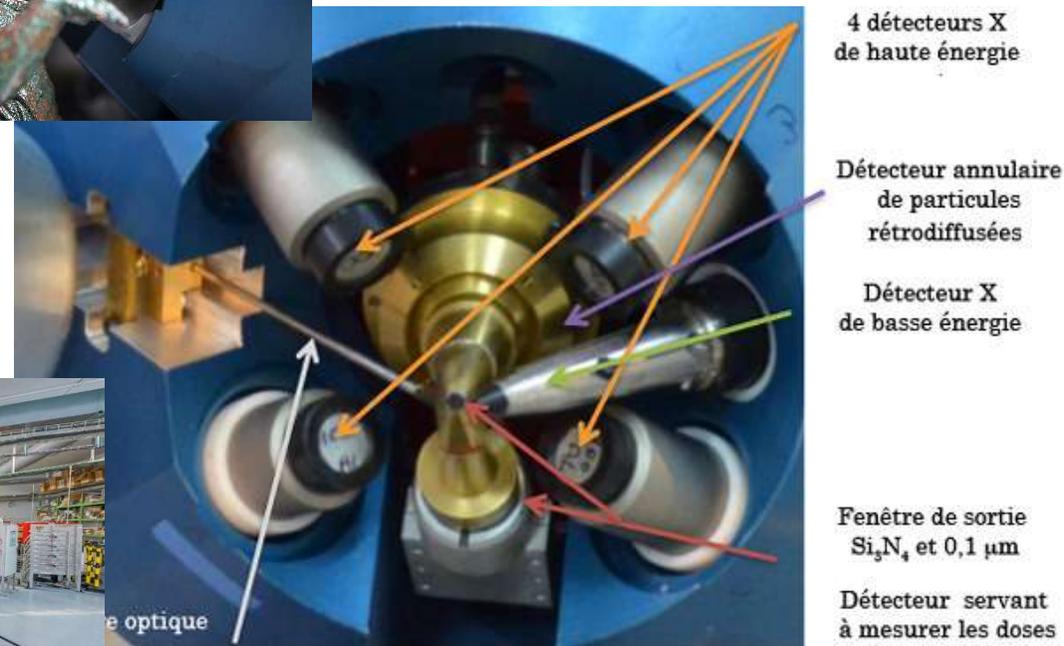
New AGLAE Louvres // MOSAIC // LEEL // ANAFIRE // AIFIRA //



## Particle Induced X-rays Emission PIXE



## New AGLAE Tandem



X-ray energy ~ Z<sub>sample</sub>



# A technics for datation : AMS (200kV, 3MV, 5MV)

## AMS=Accelerator Mass Spectrometry

Measuring the Ratio  $^{14}\text{C}^*/^{12}\text{C}$  in sample

**Warning: elimination molecules CH**

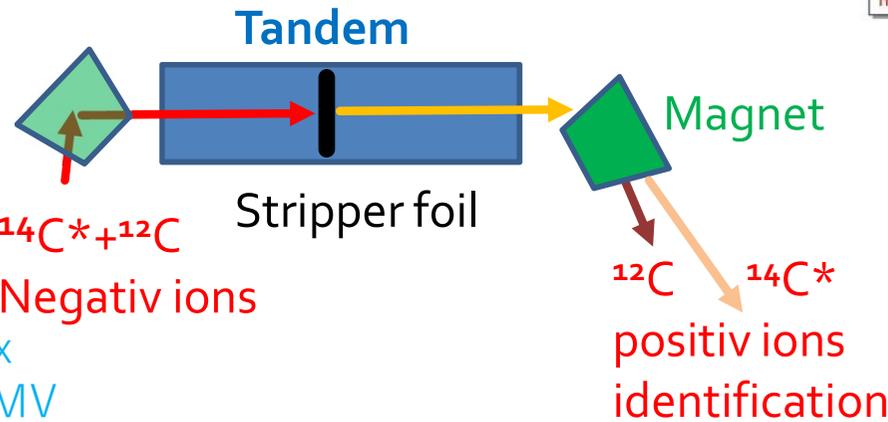
ARTEMIS@Saclay  
Tandem 3 MV



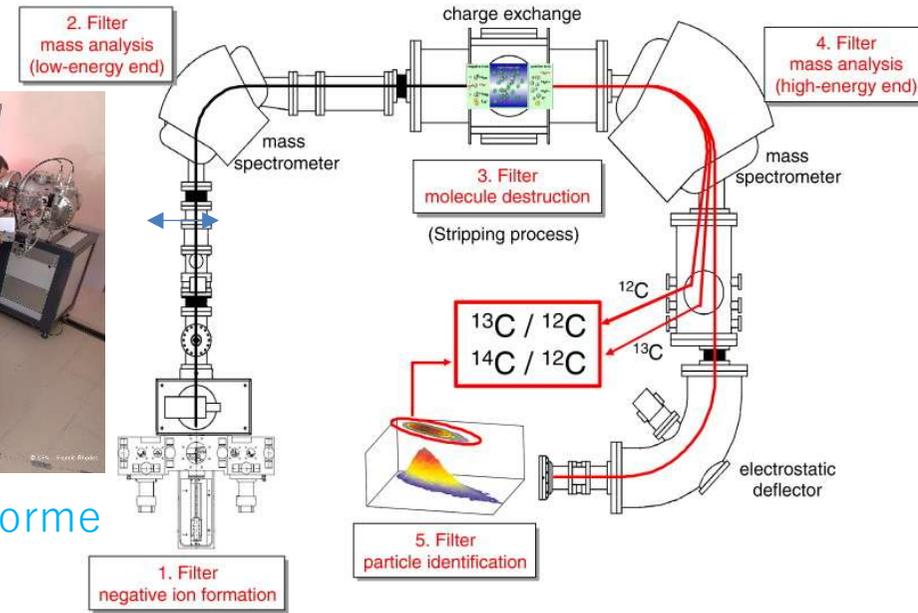
200kV



ECHoMICADAS MHSN@L'orme



## Micro Carbon Dating System\*



Natural Sample  
with  $^{12,13}\text{C} + ^{14}\text{C}^* + (\text{CH} + \text{CH}_2 \dots)$

[\\*MICADAS, NIMB Vol 259, N°1, 2007, P 7-13](#)



ASTER@Aix  
Tandem 5 MV

**CERN GENEVE** (5 synchrotrons , 3 linacs,...

**SACLAY** ( 1 synchrotron light source , 2 e-linac , 2Van de Graaff, 1 RFQ p) : 6

**ORSAY** ( 2 cyclotrons, 4 elinac , 3 Van De Graaff) : 9

**CAEN** ( 7 cyclotrons, 1 synchro-cyclotron, 1 Linac ) : 9

**NICE** (1 synchro-cyclotron , 1 cyclotron ) : 2

...

# Sites with many accelerators



LINAC4 (H-)

LINAC2 (Pb<sup>29+</sup>)

LINAC ISOLDE

CERN LEIR : C=78 m

CERN PS-booster C=150m

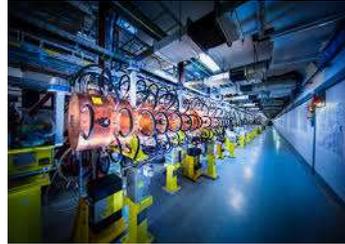
CERN PS : C= 628m

CERN SPS : C= 7000 m

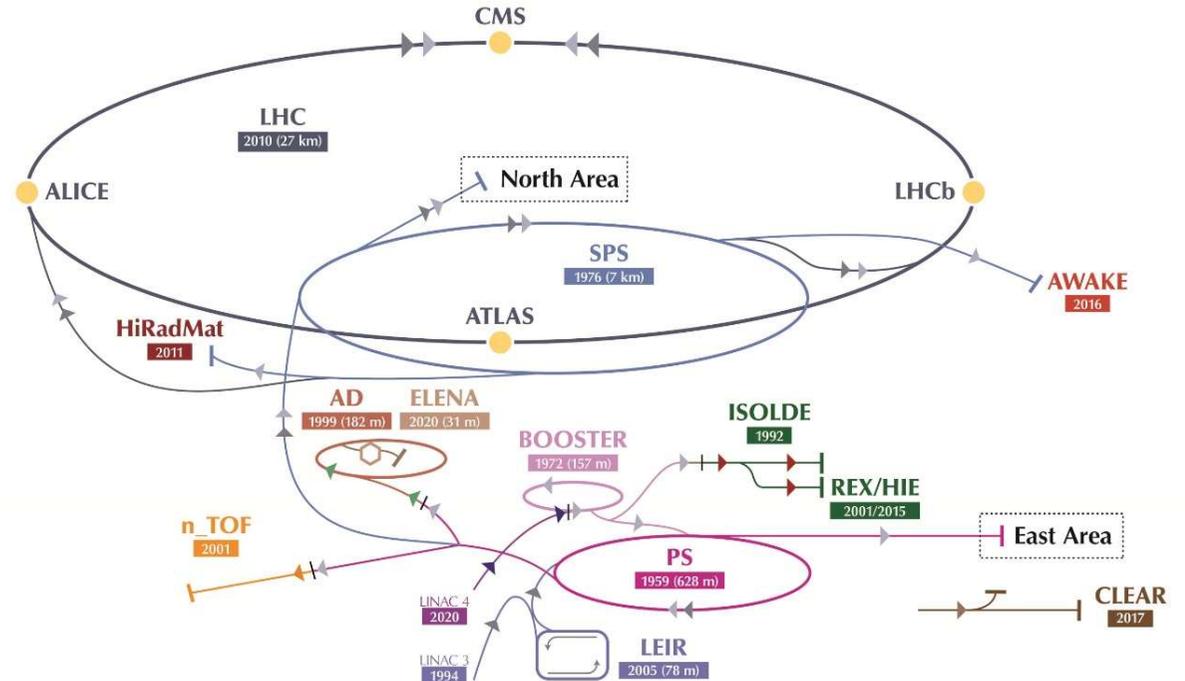
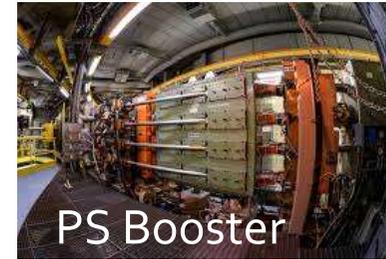
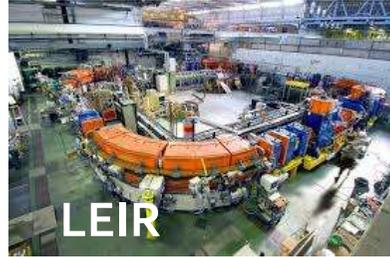
CERN LHC : C= 27000 m

Rings AD+Elena (Decelerators)

LINAC e CLEAR : Clic Test facility



## CERN Genève





## Saclay & Bruyeres le Chatel

SOLEIL (Synchrotron light sources  $e^-$ : 2,75 GeV)

LEEL ( ions 3.75 MV) : [Materials synthesis & caracterisation](#)

LIONS lab (ALIENOR :  $e^-$  LINAC 10 MEV // ACCIR : 60 keV egun )

[Nanostructured materials](#)



APOLLON @L'Orme Des Merisiers

(pulsed lasers : 10 PW [acceleration electron multi-GeV,...](#))

ARTEMIS LMC\_14 (ions 3MV) : [Datation C14, geochimie](#)

ECHOMICADAS MHSN @L'Orme Des Merisiers

IPHI-RFQ 3MeV Proton : [neutron](#)

[ELSA @Bruyeres \(e-linac 30MeV \)](#)

[CEA DAM @Bruyeres \(7MV + 4MV\): Defense, nuclear physics](#)



SOLEIL@Saclay



ARTEMIS@Saclay : 3MV

# Sites with many accelerators

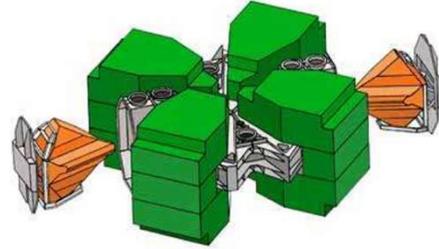
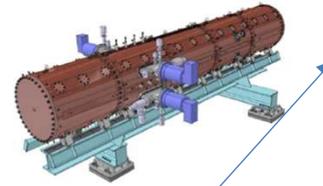


## CAEN, NORMANDY

(Labs: GANIL, CIMAP, LARIA, LPC CAEN, CYCERON University, Cancer treatment ARCHADE)

GANIL : ions 0.1MeV/A-95 MeV/A , 5 cyclotrons  
 GANIL LINAC: ions 2 RFQ+ 1 Linac (40 MV)  
 GANIL NFS : neutron beams

**Nuclear physics , Atomic physics , Materials under irradiation**  
**Radiobiology (new therapies), Industrial applications**  
**R&D on accelerators & detectors**



CYCERON : production radio isotopes, cyclotron 18 MeV  
 ARCHADE : proton treatment 1 synchro cyclotron 230 MeV  
 ARCHADE : Carbon, proton 1 cyclotron up to 400 MeV/A  
 GANIL ARIBE : ion qx30 kV , beamlines+sources



## Ion accelerators in France ~60 accelerators (

Medical Applications (radio-isotopes, treatments)  
Research facilities

### **Vast majority of the particle accelerators are for the medical applications**

Radio-isotopes production with ~30 cyclotrons (10-30 MeV H<sup>-</sup>, H<sup>+</sup>, D)  
but also research: Material science & Nuclear physics

### **Projects in construction**

**NEW GAIN at GANIL** (1 RFQ A/Q=7, ECR Ion source Superconducting )  
collaboration : CEA, LPSC@Grenoble

**C400@ARCHADE CAEN** : Carbon at 400MeV/u , IBA

**IPHI-Compact Accelerator Neutron Source@ Saclay** : 3 MeV proton RFQ

References : SfP , brochure « les activités accélérateurs » , Vincent Le Flanchec - Laurent Nadolski  
other talks in this meeting G. Gaubert (ARCHADE), Jacques Balosso (medical Accelerators)

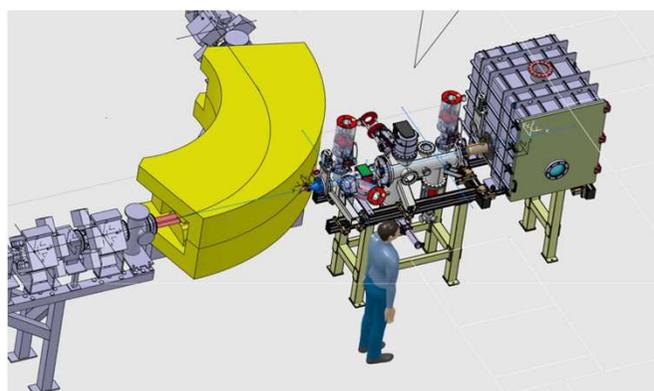
# One example of a societal application :

## SAGA: SPACE APPLICATIONS AT GANIL

New beam lines for radiation hardness testing of electronic components

Final Goal: up to 7 beams simultaneously at GANIL (research AND industry )

A new compact beam line for Cocktail beam



Cocktail beam :

Delivering successively a set of 10 different ion beams (Xenon, Kr, Fe, Cu, ...Al,Ne,N)  
Tuning time <10 min

New beam lines for Xenon beams in parallel

Project :  
3 simultaneous irradiations in parallel with 3 Xenon charge states:

$Xe^{48+}$ ,  $Xe^{51+}$ ,  $Xe^{53+}$

