



GDR SCIPAC

SCIences of Particle ACcelerators

Ion Accelerators in France

B. Jacquot CNRS, GANIL

GdR SCIPAC meeting

Genoble - march 2026

Questions to be addressed :

How many accelerators in France (versus electron machines) ?

What are the main applications for the ion accelerators ?

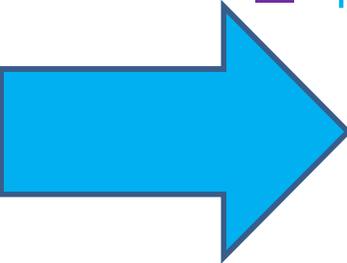
What are the technologies for medical applications ?

The electrostatic machines versus the Radio frequency machines ?

Are the laboratories linked within a network ?

What are the important site for ion accelerators in France?

- Particle Accelerators (>1MV) in the world (>20000)
 - Particle Accelerators in France (~500)
 - Electron Accelerators in France (~450)
 - Ion accelerators in France (~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 (electron-Linac 6-20 MeV)
- 2) Radionuclides production with cyclotrons (10-30 MeV H⁻, H⁺, 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 accelerator in France Troyes (10 MeV), few $^{60}\text{Co}^*$ sources



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)

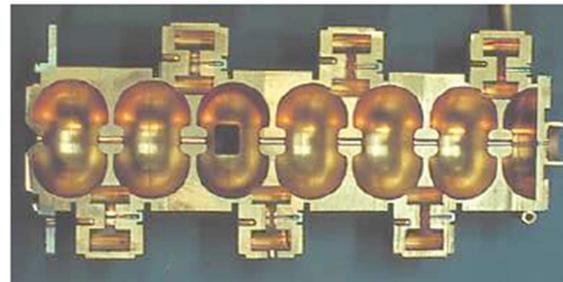
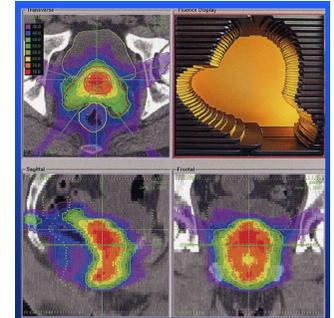
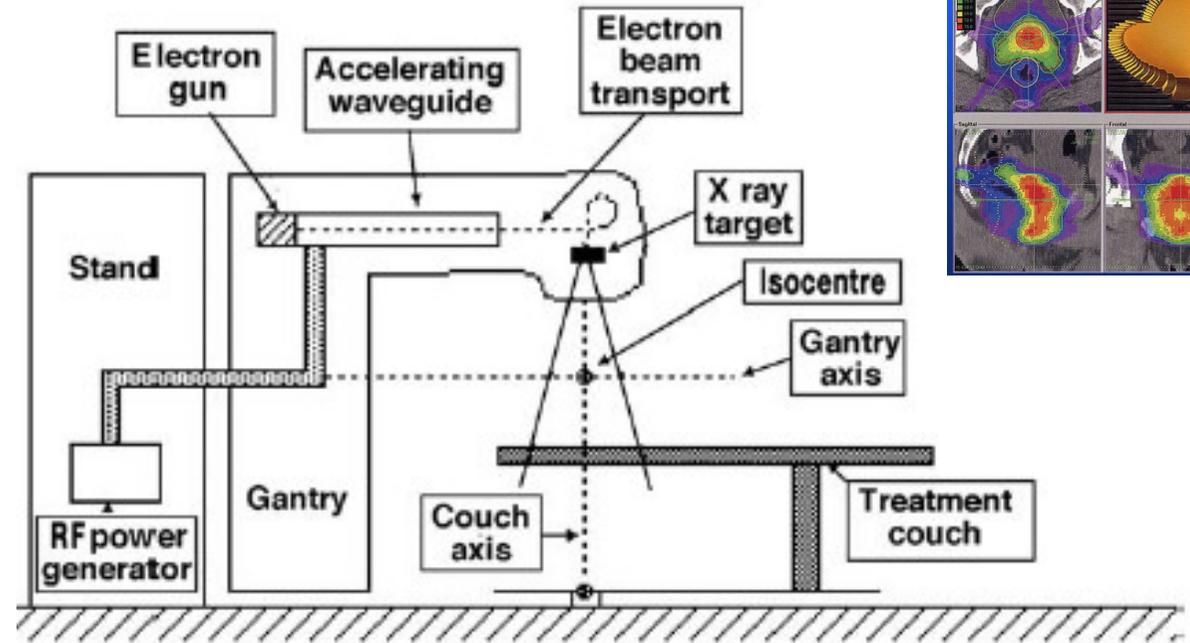
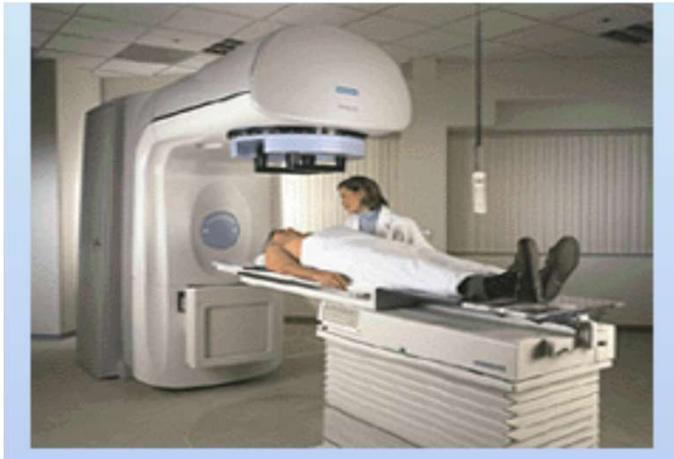
APOLLON @Saclay (pulsed laser 10 PW, acceleration electron multi-GeV)

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 : >30 (Nuclear Physics, Atomic physics, Material science, Medical)

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

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

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

MOSAIC@Orsay (190kV, 2MV, 4MV,400kV), ALTO@orsay (Tandem 14.5 MV)

SAFIR@PARIS-Jussieu (Van De Graaff 2.5 MV), AGLAE @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)

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), CEMHTI@Orléans (VdG 3MV)

JANNU-Saclay (Tandem 2MV, VdG 2.5 et 3MV)

M >4 amu

60 Ion Accelerators in France

Acceleration Technology in France

| | | |
|-----------------------|---|-------------------------------------|
| 70% cyclotrons | : | 40 (Cyclotrons+SynchroCyclo) |
| | | 2 Linac (without Cern) |
| 30% electrostatic | : | 8 Tandems Van De Graaff |
| | | 8 Van De Graaff |
| | | 3 Electrostatic ~ 200kV-400kV |

Topics, Science

+ material science +...

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

65% : **32 for radionuclides production**

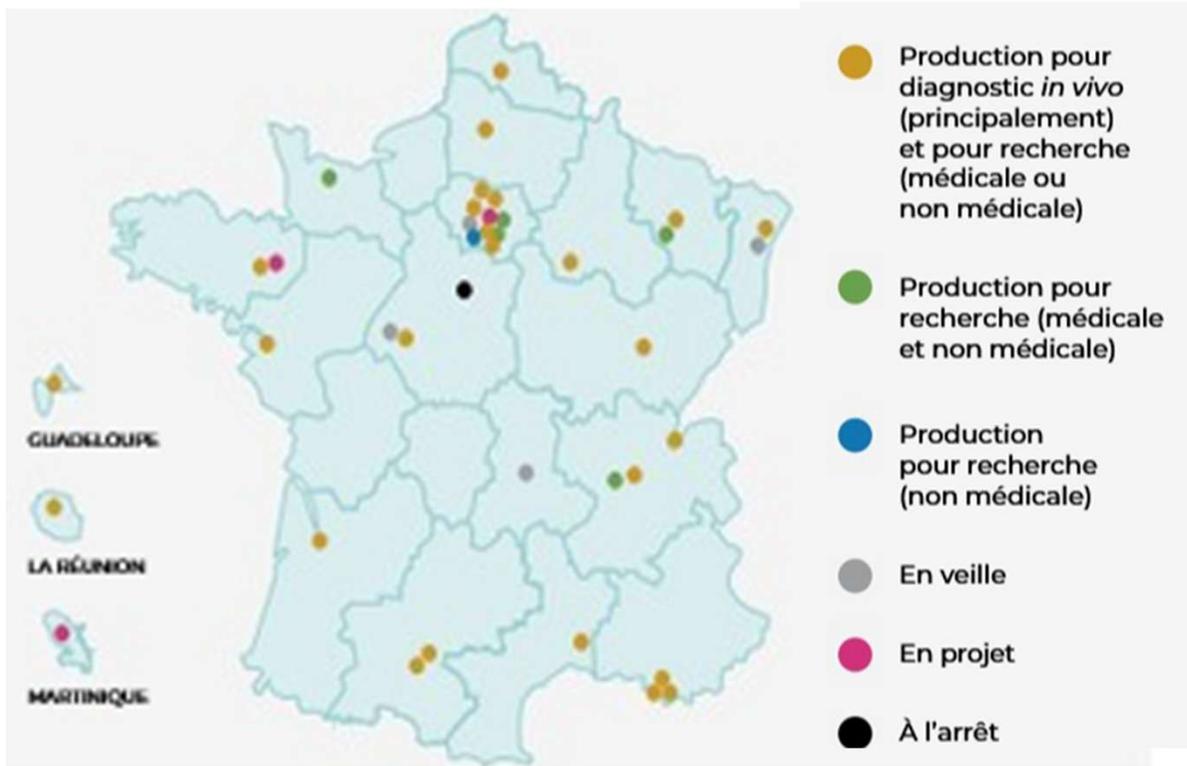
10% : **6 for Radiobiology, Medical research**

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



beam time
~75% MEDICINE

Cyclotrons for medical radionuclides

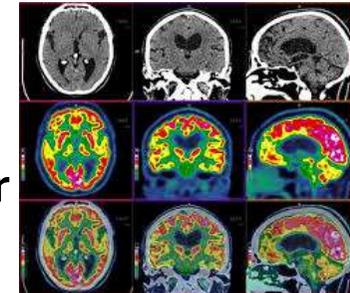


* Info from: rapport ASN2023

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

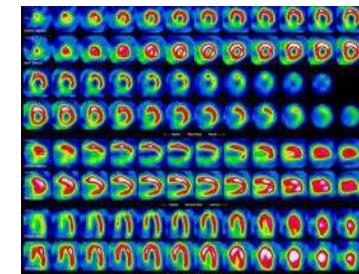
TEP Camera :
fluor F^{18} , carbon C^{11} , O^{15}

Brain tumor



Scintigraphy :
thallium 201, iode 123, gallium 67)

myocard



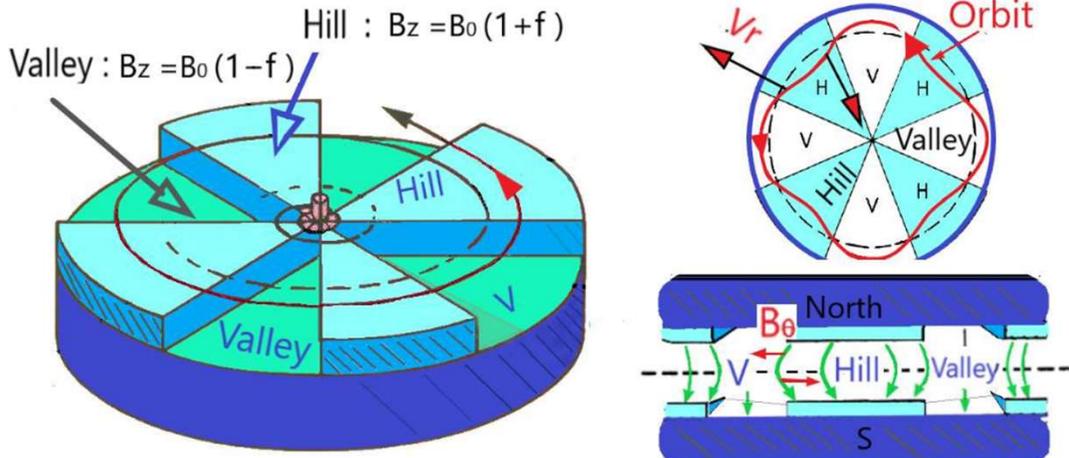
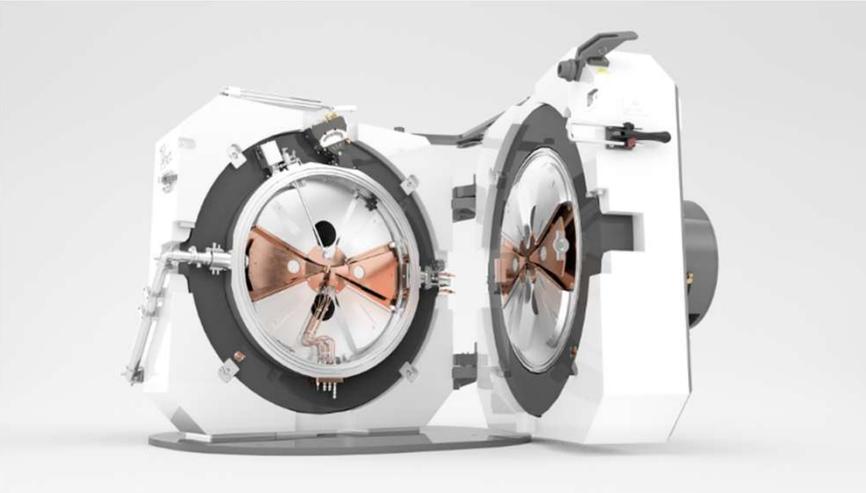
2-3 cyclotrons for research

+ ARRONAX 70 MeV protons
+ CYRCé 25 MeV, Cyceron 18MeV

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)



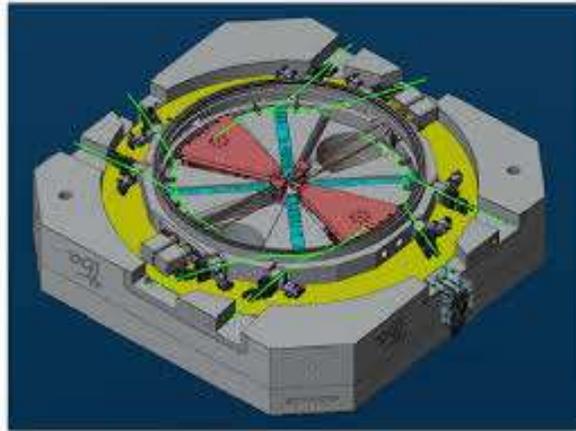
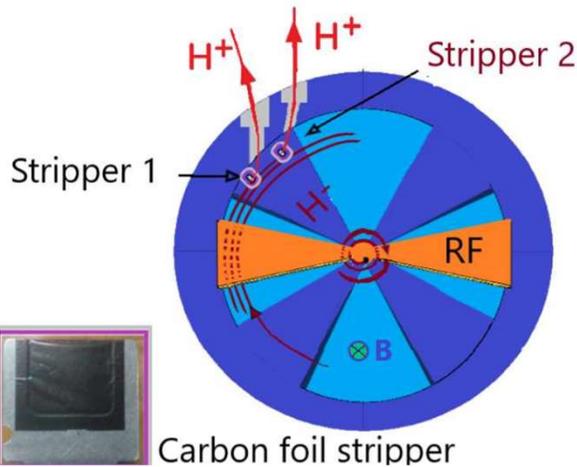
$B_z = F(\theta) \Rightarrow$ azimuthal field component

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

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

Medical cyclotrons in France

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



H⁻ = Easy extraction
(no High Voltage deflector : fragil)

Several simultaneous 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⁺
=> 2.5 MeV/A D⁺



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

A moving belt (nowaday pelletron)

Charge accumulation

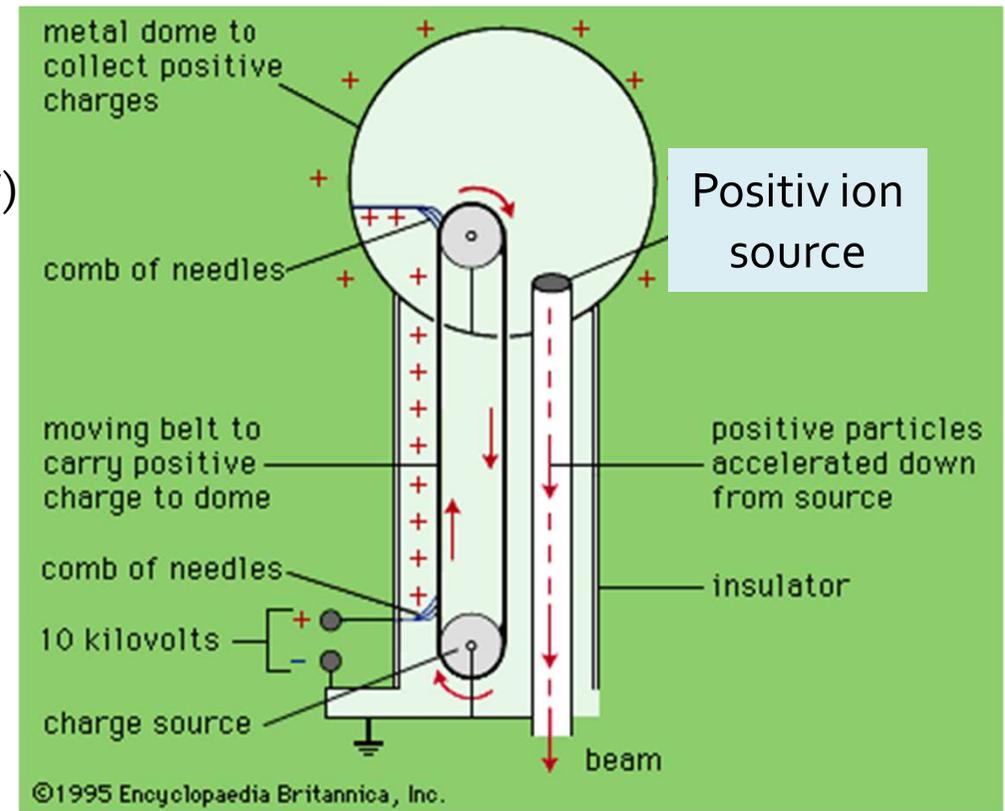
Static electric field

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

IJCLAB/ Andromede (4MV Van de Graff)



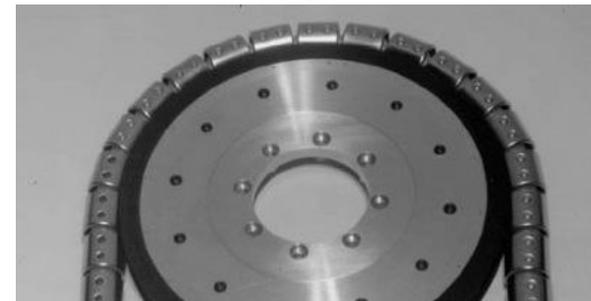
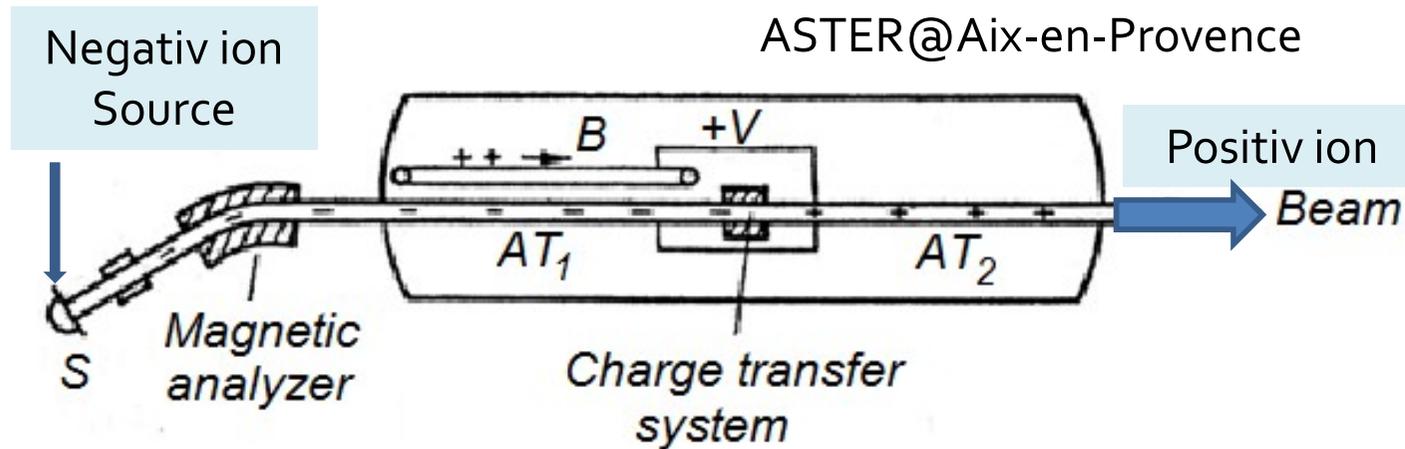
AIFIRA@Bordeaux



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) \Rightarrow Au (1.2 MeV/u) : # 30 Beams

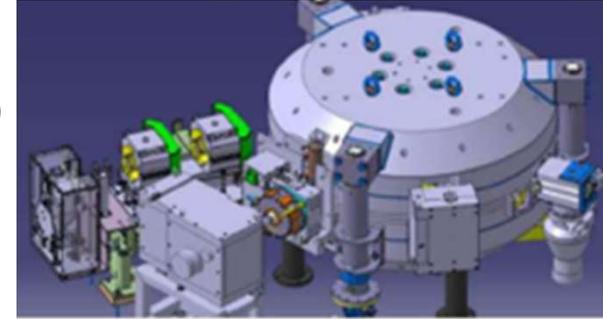
Cyclotrons with Larger energies for treatment or research

Treatment :

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

LACASSAGNE @ NICE (SynchroCyclotron K=230 MeV)

very compact machine , s.c. 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

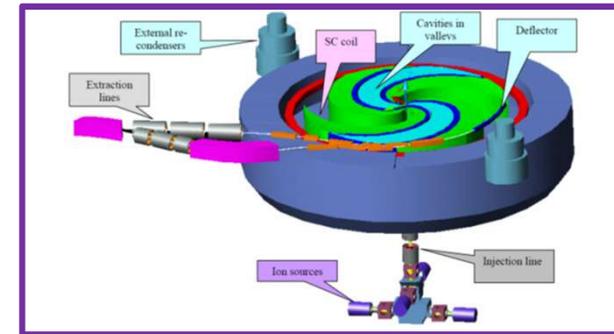
A big project : IBA C400 CYCLHAD@ CAEN (Cyclotron for Carbon K=1600 MeV)

Hadron therapy with a very compact machine

Research radio-isotopes

ARRONAX@Nantes (Cyclotron K=70 MeV)

CYRCé@Strasbourg (Cyclotron K=25 MeV)

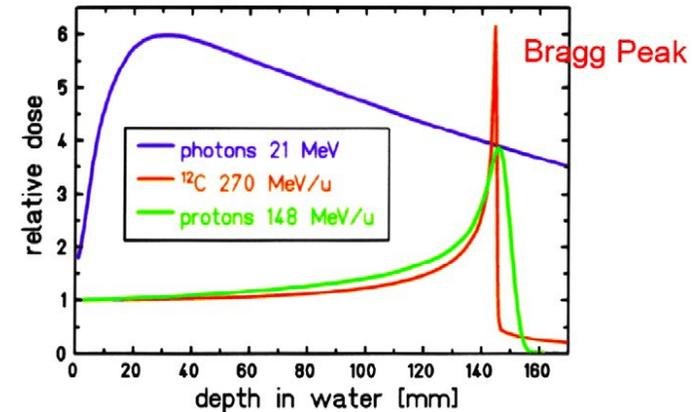


New Ion Accelerator for medical applications

C400_IBA : 400MeV/A $^{12}\text{C}^{6+}$ / 260 MeV Proton
Hadron therapy with a very compact machine

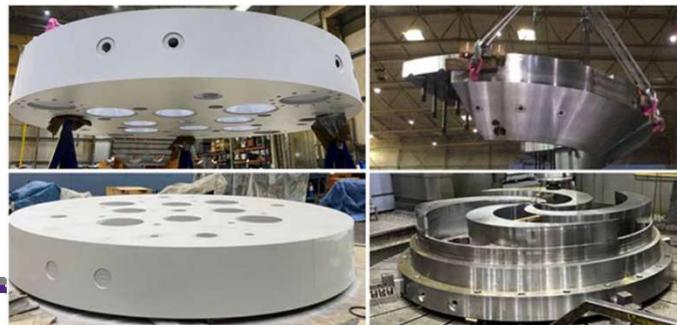
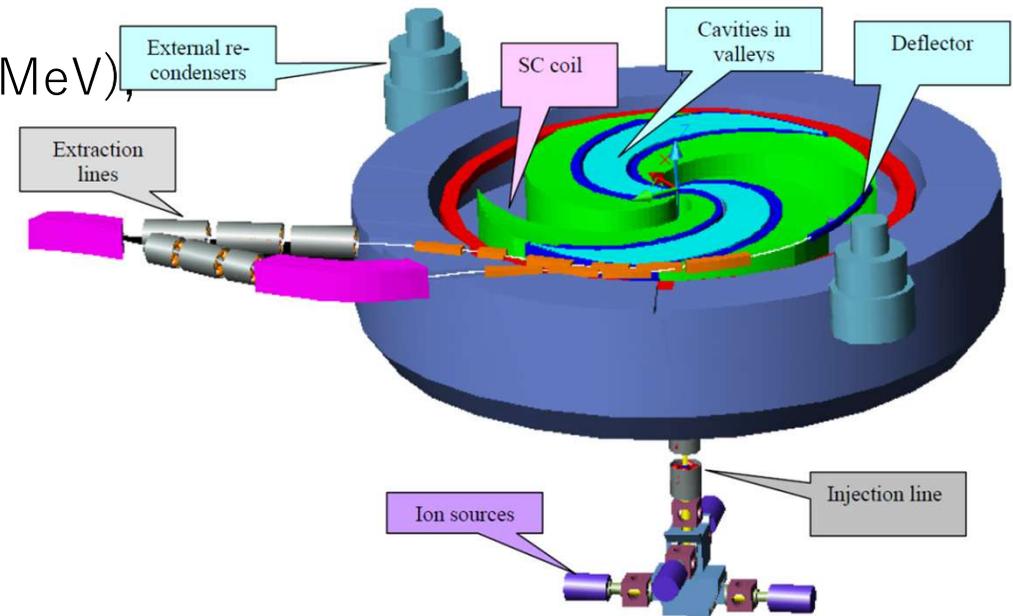
Isochronous cyclotron K=1600 MeV; 660 tons

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 : $^{12}\text{C}^{6+}$, 4He^{2+} , H_2^+ (molecule 260 MeV)



2024-25 :

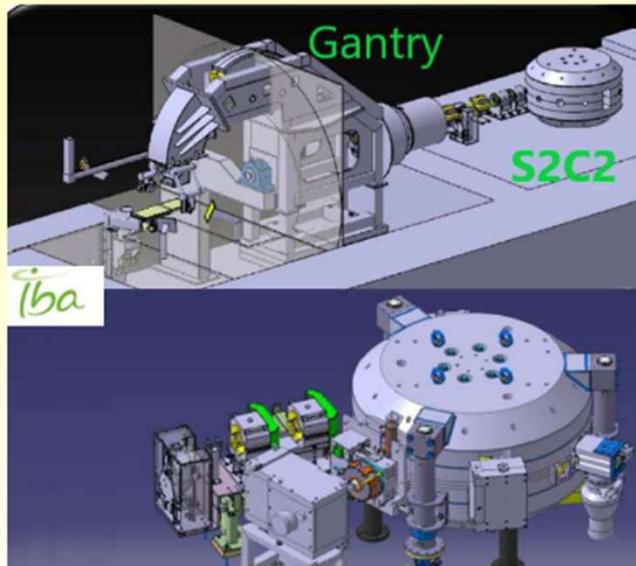
First model C400 being installed in **France**
(Caen , Normandy, 2026 first cooling)



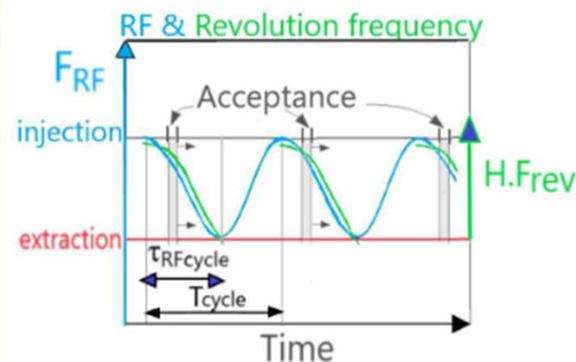
March 2026

New Ion 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

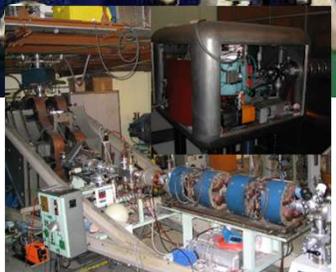
Beam is pulsed (low average
 intensity) But very compact...

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

Heavy Ion Accelerators in France



ALTO@IJCLab



Genesis@LPSC



CYRCé@Strasbourg



Research platform
mosaic
IJCLab



ARTEMIS@Saclay



SAFIR



7MV DAM



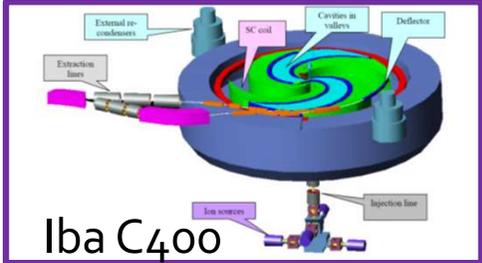
DESIR



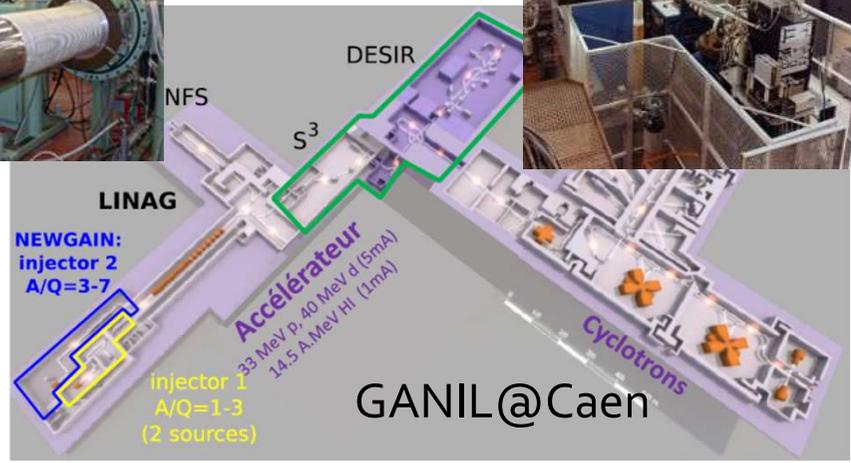
ARRONAX



New AGLAE



Iba C400



GANIL@Caen

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,400kV)

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

AIFIRA@Bordeaux(VDG 3.5MV Light ions)

AGLAE@Paris-Louvres (Tandem 2MV)

SAFIR@JussieuPARIS(Van De Graaf 2.5MV)

CEMHTI@Orléans (Van De Graaf 3MV)

JaNNus-Saclay (VDG 2.5 ,3 MV, Tandem 2MV)

Environment, Datation (AMS, ^{12,14}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, CYCLHAD@Caen (x2), CPO@Orsay

~Nuclear physics

GANIL@Caen (5 cyclo.+ 1 Linac)

ALTO @Orsay (Tandem 14.5 MV)

DAM@ Bruyeres (4MV+ Tandem 7MV)

GENESIS@Grenoble (200 kV)

AMANDE Cadarache ASNR (Tandem 2MV)

CERN Isolde (LINAC4+PSB+LINAC Isolde)

NENUPHAR DAM@Bruyere (7MV)

Medical research, Radiobiology, Isotope research

ARRONAX

CYRCé

CERN (ISOLDE) MEDICIS

Industrial applications, Commercial irradiations

Electronic testing, Space application,...

[The French network émir&a: irradiation and analysis of molecules and materials](http://emira.in2p3.fr)

Web: emira@in2p3.fr

A link between ~15 accelerators (6 sites) and 11 laboratories

A unique organization :

- Large variety of accelerated beams (ions and electrons)
- Many complementary technics for analysis
- A unique link between physicists, chemists, Engineers
- A Coordination for access to irradiations & analysis sites

Ion & electrons machines



Ion Accelerators in France : Focus on émir&a



Ion & electrons machines : *see talk Nathalie Moncoffre (IPNL)

Mosaic@Orsay: IRMA (190 keV), ARAMIS (Tandem 2 MV)

& **Andromède (VdG 4 MV)**, ... futur Electrostatic 400kV

LEEL@Saclay : Microsonde ionique, VdG 3,5 MV

AIFIRA@Bordeaux: **Electrostatic 3 MV**

SAFIR@JussieuPARIS : **VdG 2.5 MV**

GANIL-ARIBE@Caen : qx 20kV

GANIL-IRRSUD@Caen : cyclos C01 or C02 (0.1-1MeV/u)

GANIL-SME: cyclos C0+CSS1 (4-13.7MeV/u)

GANIL-D1orG4@cyclos C0+CSS1+CSS2 (24-95MeV/u)

CEMHTI@Orléans : **Pelletron 3 MV**

JANNuS Saclay : **EPIMETHEE (VdG 3 MV)**,

JAPET (Tandem 2MV), **PANDORE (2.5 MV)**

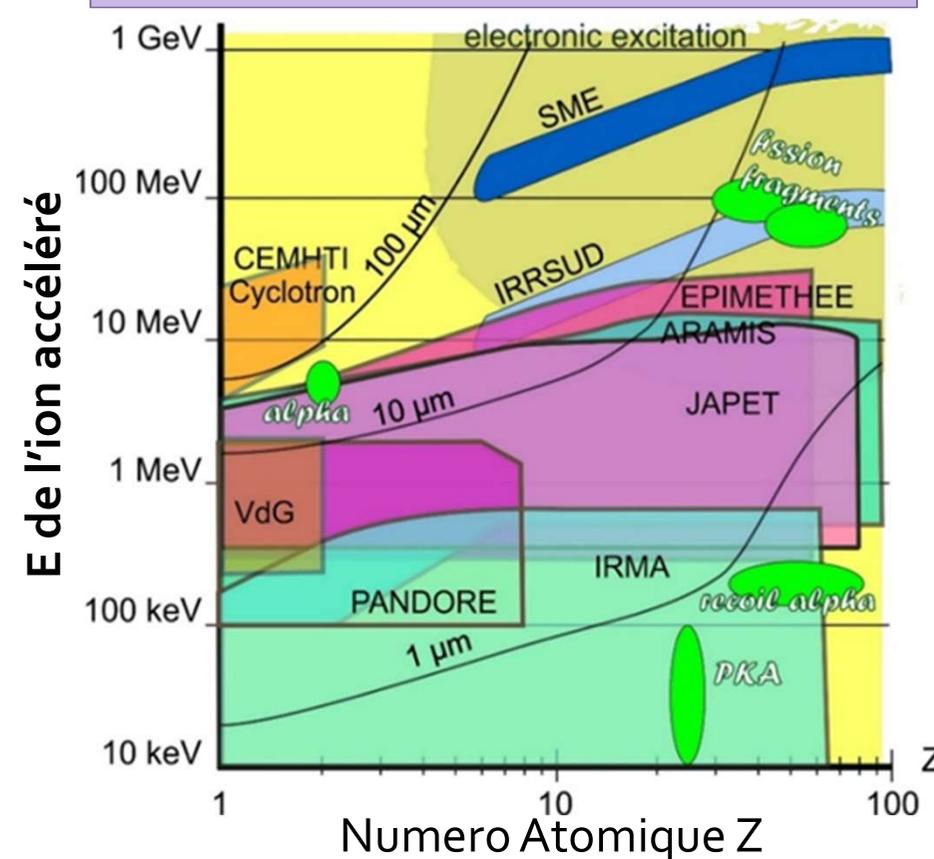
NIMBE -Alienor@Saclay: pulsed electrons ns, 10 MeV

SIRIUS: electrons 2,5 MeV

Electron Microscope **HVEM@Saclay**: μ faisceau 1,2 MeV 1

Elyse@Palaiseau : linac electrons ps pulsé, 9 MeV

Irradiation
→ Very large domain in Z – energies
Z = 1 -> 92 & from 10 keV up to GeV



Ion Accelerators in France : Focus on émir&a



Beam time for users in 2025-2026:

| Platform Ions & electrons | PRICE for users | Beam time per year |
|--|------------------------|--------------------|
| ALIENOR | 3 k€/week | Few weeks. |
| CEMHTI | 60 €/1 hour | 10 weeks |
| GANIL-SME GANIL-IRRSUD GANIL-G4 or D1_HE | Free academic research | ~60 days |
| JANNU-S-Orsay | 2000€/experiment* | 5 (+1) weekz |
| Microsonde LEEL | Free academic research | 10 weeks |
| ANDROMEDE | 2000€/experiment* | Few weeks. |
| ELYSE | Free academic research | 50 days |
| SIRIUS | 1500 €/day | 50 days |
| JANNU-S-Saclay | 2000€/experiment | 3 weeks |
| HVEM | free | 5 day |
| SAFIR | 300 €/ 4Hoo shift | Few weeks. |
| | | |

*talk Nathalie Moncoffre (IPNL)

-Call for propopals every year :

On <https://emira.in2p3.fr/>

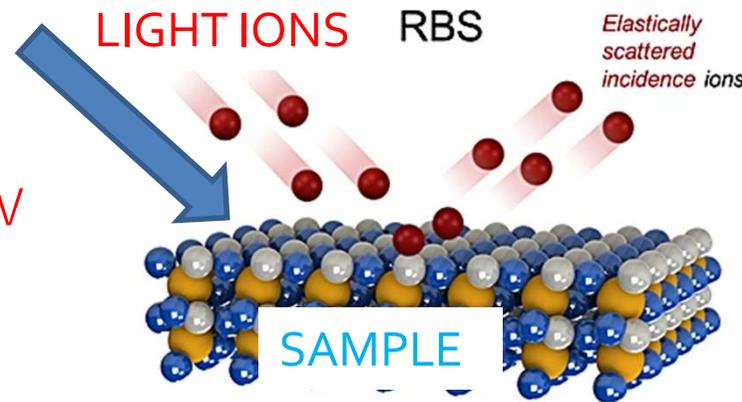
-Science : Evaluated by 2 experts

**-Technical : Evaluated by each
accelerator platform**

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

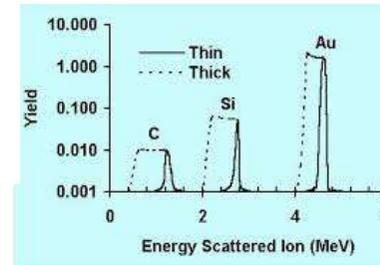
MOSAIC@Orsay (190kV, 2MV, 4MV) // LEEL@Saclay (3.75 MV) // New AGLAE@Paris (Tandem 2MV)
 AIFIRA@Bordeaux (3.5MV ions Legers)//SAFIR (2MV)

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



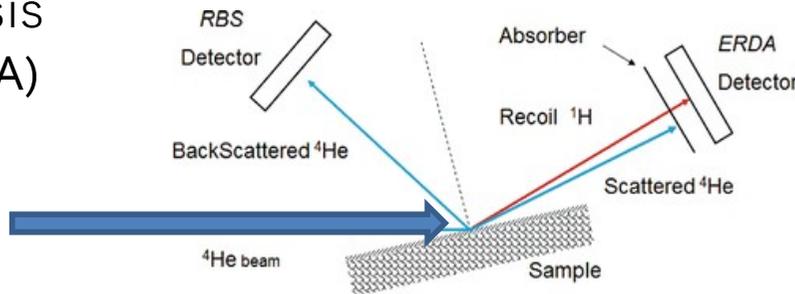
Quantitative analysis for RBS

- Kinematic Factor ($M_{projectile}, M$)
- Cross section ($M_{projectile}, M, \theta$)
- Energy losses (depth, $Z_{projectile}$)

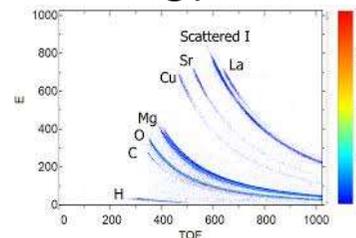


Not good for light elements

Elastic Recoil Detection Analysis (ERDA)



Energy ToF



Quantitative analysis ERDA

- Low scattering angle θ
- good for light elements
- Complementarity with RBS, PIXE

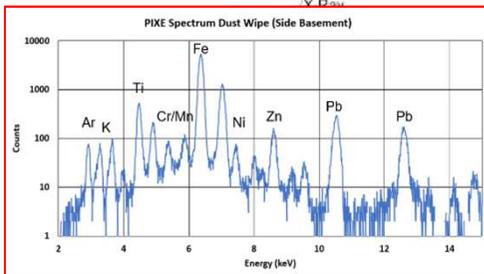
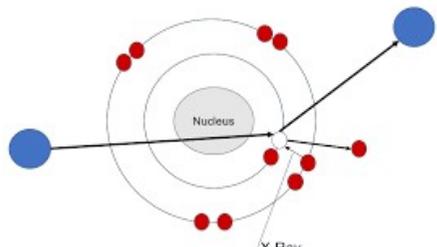
Ion beam Analysis with Accelerators

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

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



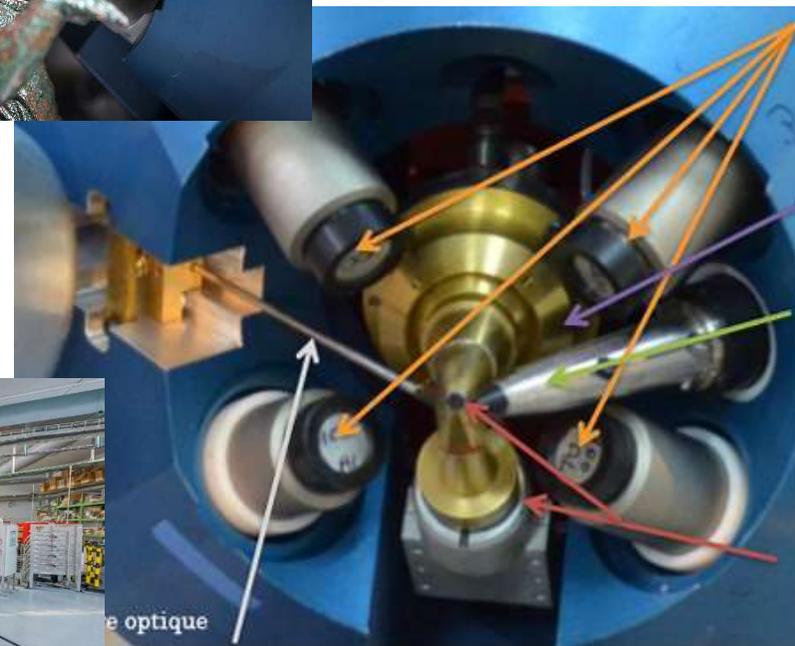
Particle Induced X-rays Emission PIXE



New AGLAE Tandem



See talk Thomas Calligaro



4 détecteurs X de haute énergie

Détecteur annulaire de particules rétrodiffusées

Détecteur X de basse énergie

Fenêtre de sortie Si_3N_4 et $0,1 \mu\text{m}$

Détecteur servant à mesurer les doses

X-ray energy $\sim Z_{\text{sample}}$

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



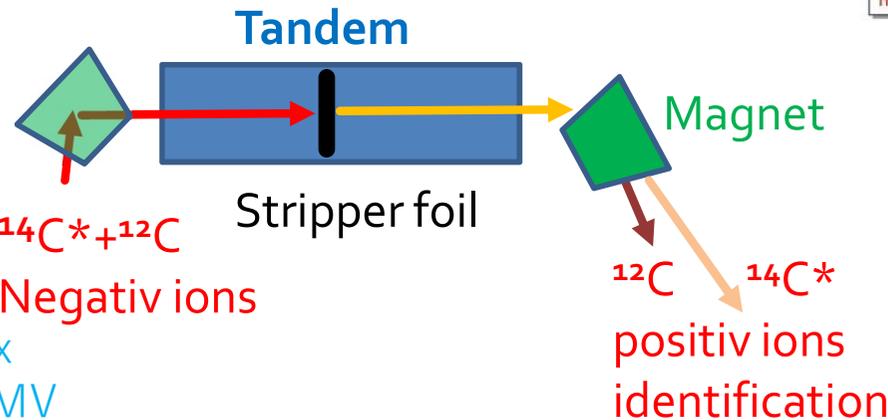
200kV



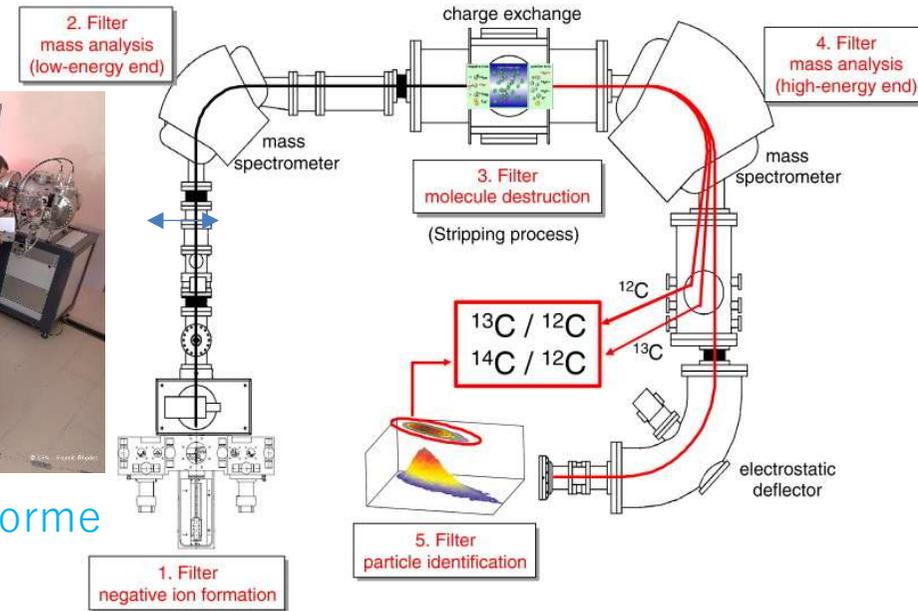
ECHoMICADAS MHSN@L'orme



ASTER@Aix
Tandem 5 MV



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](#)

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

SACLAY (1 synchrotron light source , 2 e-linac , 5 electrostatics, 1 RFQ p) : 9

ORSAY (2 cyclotrons, 4 elinac , 3 Van De Graaff, 190kV, 400kV) : 11

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

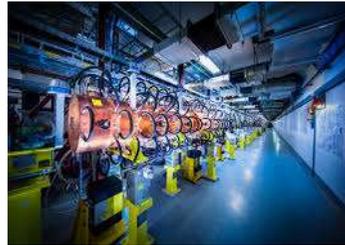
NICE (1 synchro-cyclotron , 1 cyclotron) : 2

...

Sites with many ion accelerators

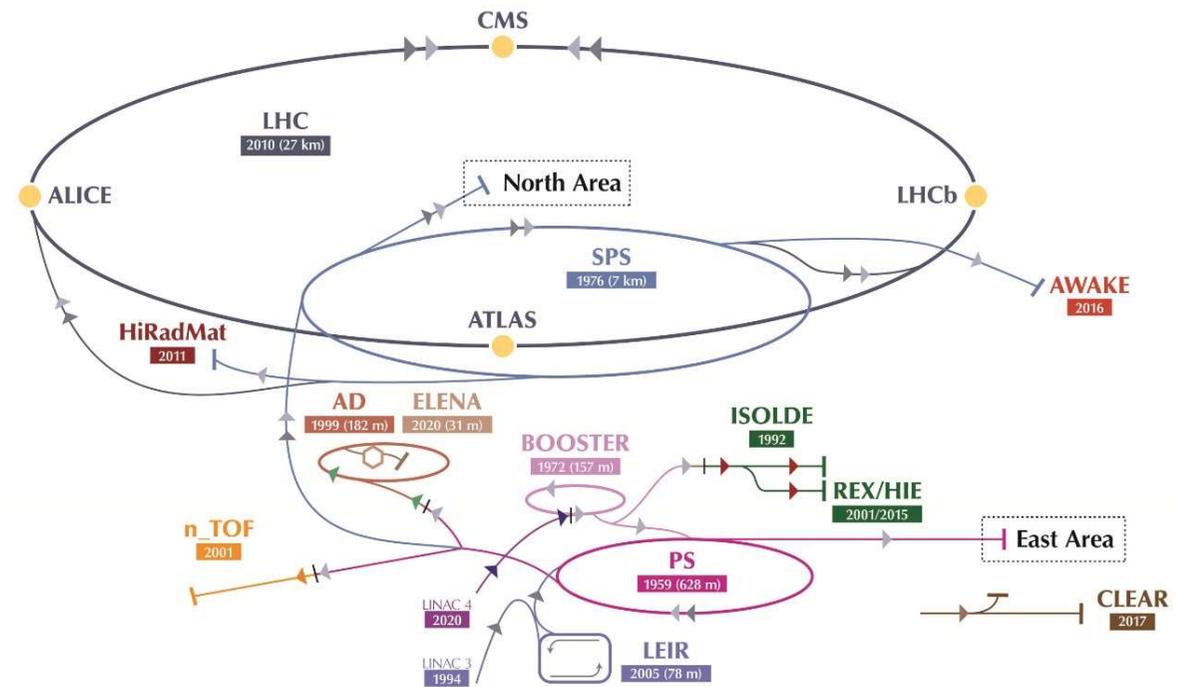
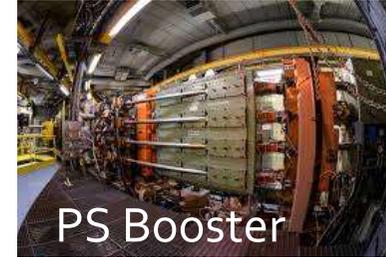


LINAC4 (H-)
 LINAC2 (Pb²⁹⁺)
 LINAC ISOLDE



CERN Genève

CERN LEIR : C=78 m
 CERN PS-booster C=150m
 CERN PS : C= 628 m
 CERN SPS : C= 7000 m
 CERN LHC : C= 27000 m
 Rings AD+Elena (Decelerators)
 LINAC e CLEAR : exClicTest facility



Sites with many accelerators :

Orsay : IJCLAB, CPO, SHFJ

ALTO (ions, Tandem 14.5MV) : nuclear physics, Applications
ALTO (electron linac 50 MeV)



CPO : proton cyclotron 230 MeV
Service hospitalier Frédéric Joliot : production isotope
(cyclotron 12 MeV)



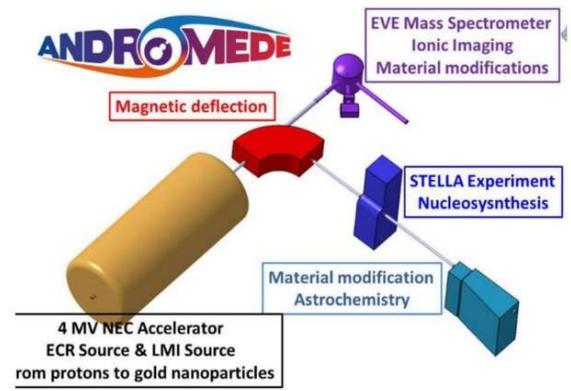
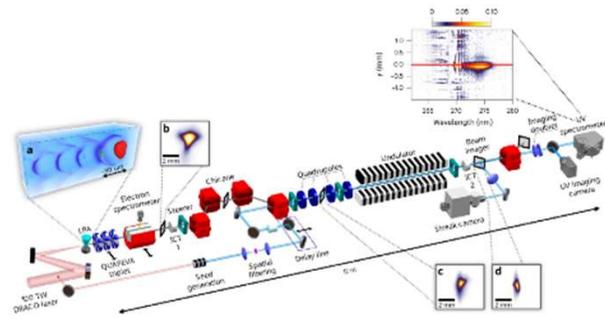
MOSAIC : ions (190kV, 2MV, 4MV, 400kV)



CLIO (50MeV e-linac, X-FEL)
ELYSE @Orsay Accélérateur d'électrons picoseconde
Isotope Separator, Sidonie (40 kV)

MOSAIC

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



Saclay & Bruyeres le Chatel

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

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

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](#)

JaNNuS-Saclay (ions VdG 2.5,3 MV, Tandem 2MV)

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

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



SOLEIL@Saclay



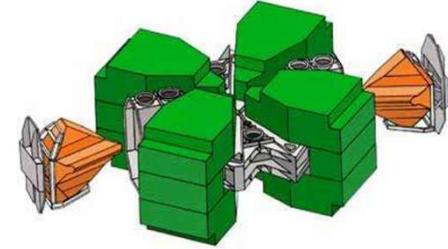
ARTEMIS@Saclay : 3MV

Sites with many accelerators : CAEN



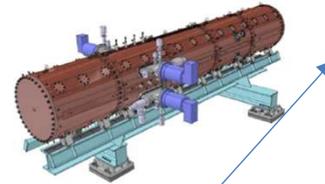
CAEN, NORMANDY

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



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
 CYCLHAD : proton treatment 1 synchro cyclotron 230 MeV
 CYCLHAD : 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⁻, H⁺, 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@CYCLHAD CAEN: Carbon at 400MeV/u , IBA

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

Implantation of 400kV electrostatic accelerator in MOSAIC@IJCLab,...

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

Question & Answers:

How many ion accelerators in France (versus electron machines) ?

> 60 machines for ion acceleration

What are the main application for the ion accelerators ?

> radio-isotopes production

What are the main technologies for medical applications ?

> 10-20 MeV cyclotron (AVF, Isochronous, H- internal source)

The electrostatic machines versus the Radio frequency machines ?

> 30% electrostatics /// 70% cyclos (RF)

Are the labs linked within a network ?

> Not all the Labs, but an important network émir&a (11 labs : 15 accelerators)

What are the important sites for ion accelerators in France?

Cern, Orsay, Caen, Saclay

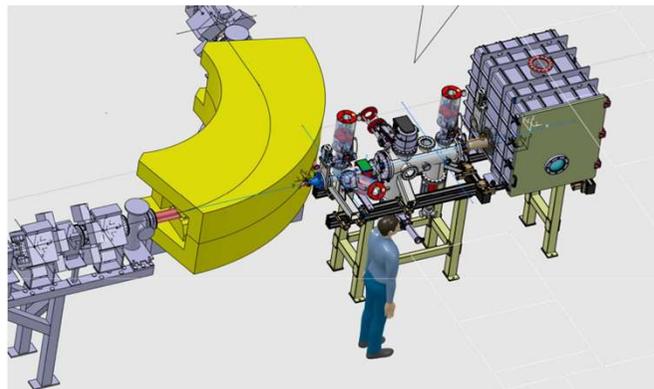
One example of a societal application :

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 beams :

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+}

