PRAE: Platform for Research and Applications with Electrons – *status report*

Imagerie et Modélisation en Neurobiologie et Cancérologie

Institut de Physique Nucléaire

Laboratoire de l'Accélérateur Linéaire

Support of

Funding :

Projet Emblématique

Programme SESAME

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Rachel Delorme on behalf of the PRAE team

PRAE Project: reminder

Multi-disciplinary site at Orsay, for R&D in subatomic physics, radiobiology and instrumentation, based on a high-performance and high-energy electron beam.

Horizon 2019/2020

Axes of the project:

WP4: Compact accelerator for high-energy electrons (VHEE)
(30 - 140 MeV)

Infrastructure and PRAE design allows an upgrade to 300 MeV

WP1: Subatomic physics (ProRad)

WP2: Radiobiology (eHGRT)

WP3: Instrumentation R&D

WP1: Subatomic physics experiment - proton charge radius measurement

WP2: new approaches in radiotherapy/radiobiology - grid-therapy

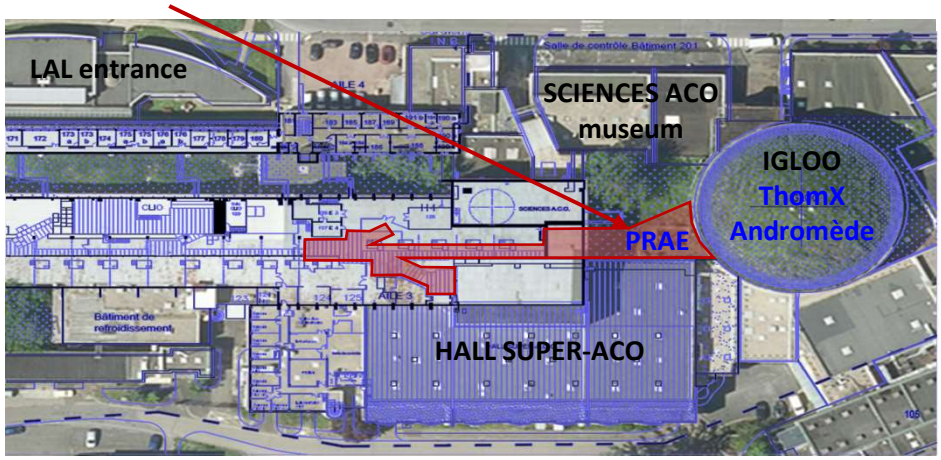
WP3: versatile instrumentation platform for detector r&D and tests

WP4: construction of the machine for the WPs required beam performance 3

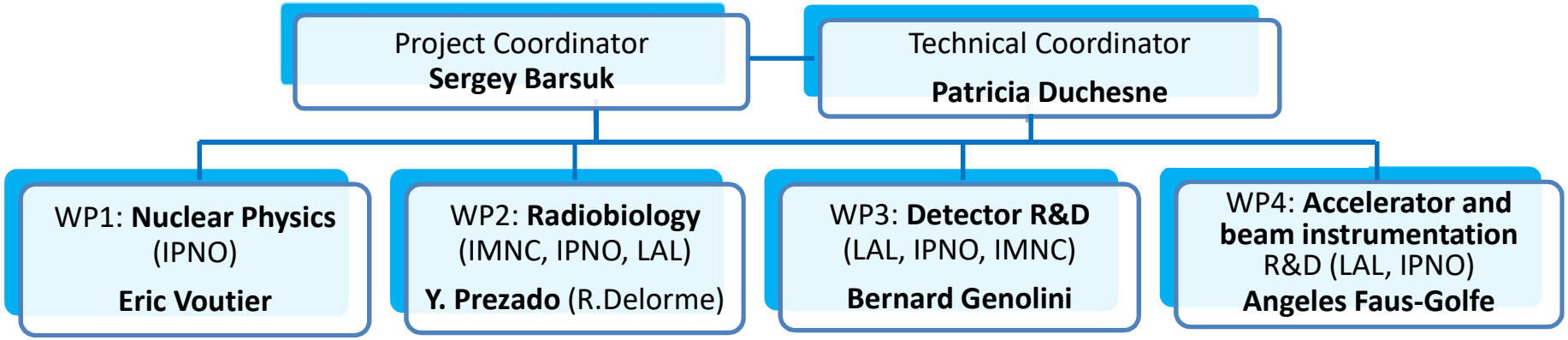
PRAE Project: reminder

Transversal project:

- Strong complementary expertise of the IMNC, IPN and LAL groups
- Re-use of the site of the former Linear Accelerator and its infrastructure



Organization:

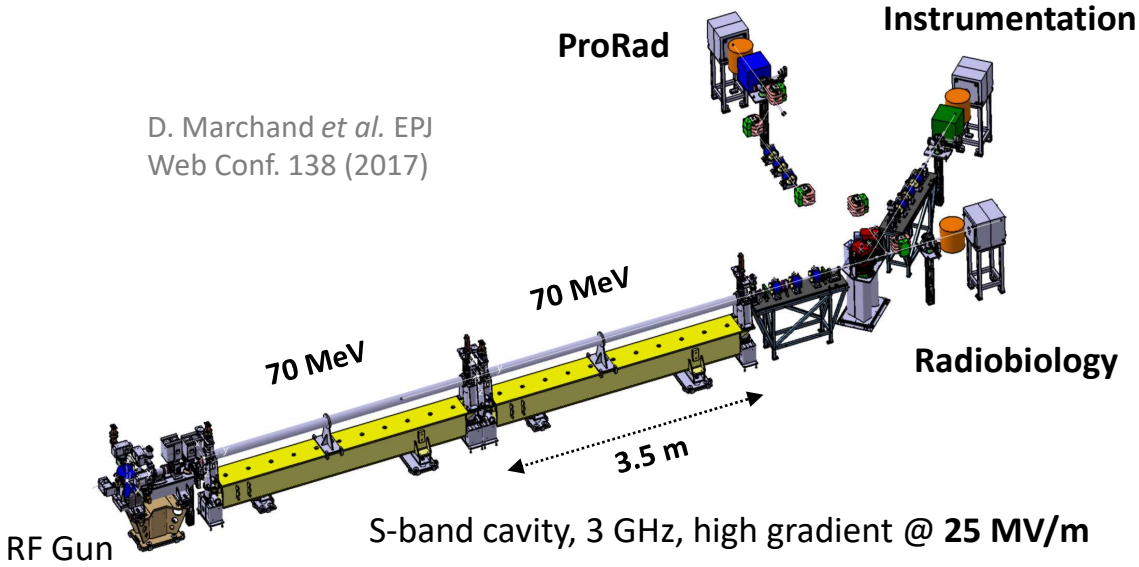


Accelerator: evolution of line design

Initial version: 3 beam lines:

Beam parameters	phase A (B)
Energy, MeV	50-70 (100-140)
Charge (variable), nC	0.00005 – 2
Normalized emittance (mm.mrad)	3-10
Repetition rate, Hz	50
Transverse size, mm	0.5
Bunch length, ps	< 10
Energy spread, %	< 0.2
Bunches per pulse	1

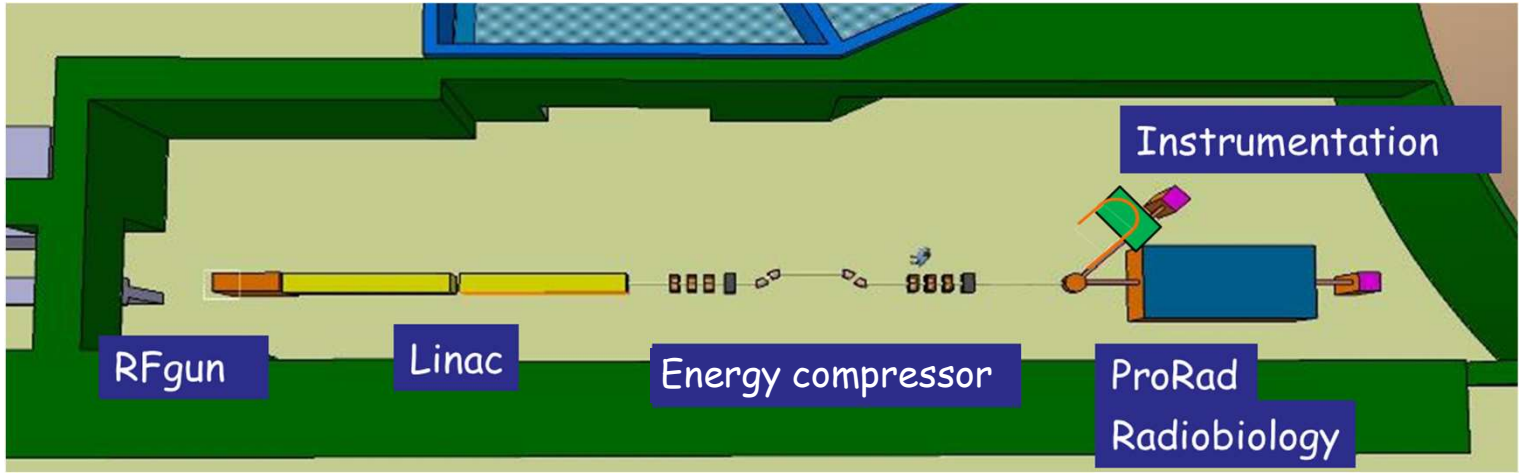
D. Marchand *et al.* EPJ Web Conf. 138 (2017)



S-band cavity, 3 GHz, high gradient @ **25 MV/m**

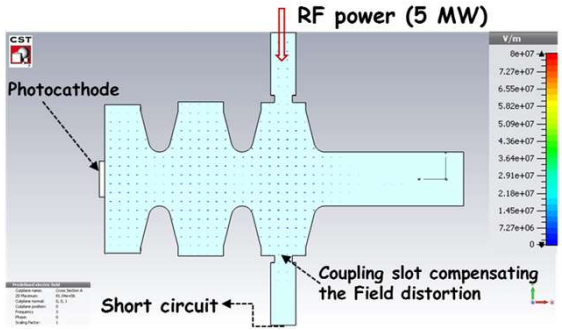
Currently:

- Optimized version, given constraints: ProRad and Radiobiology on the direct line

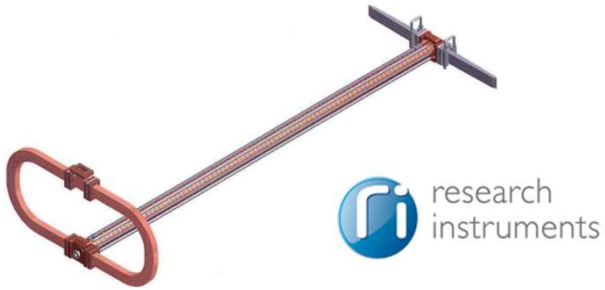


Accelerator: S-band cavities and RF gun

- **The RF gun construction:**
  - Accelerating gradient 80 MV/m at P_{in} = 5 MW.
  - LAL expertise on photo-injector (Phil, ThomX): Construction → time-delay incompatible with physics purpose…
  - Possibility to **externalize** the machining of the pieces



- **High-gradient linac:**
  - Initially: PRAE accelerator should profit from PMB-LAL accelerating section (HGAS)
  - Currently: Others options are being considered. Ex. Research Instruments GmbH, Euclid…

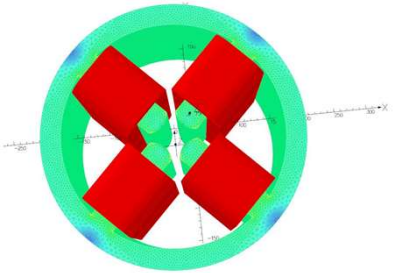


RF frequency	GHz	2.856
Repetition frequency	Hz	100
Max RF input power	MW	45
Average accelerating gradient	MV/m	23.5
Total length	m	3
Type		CG

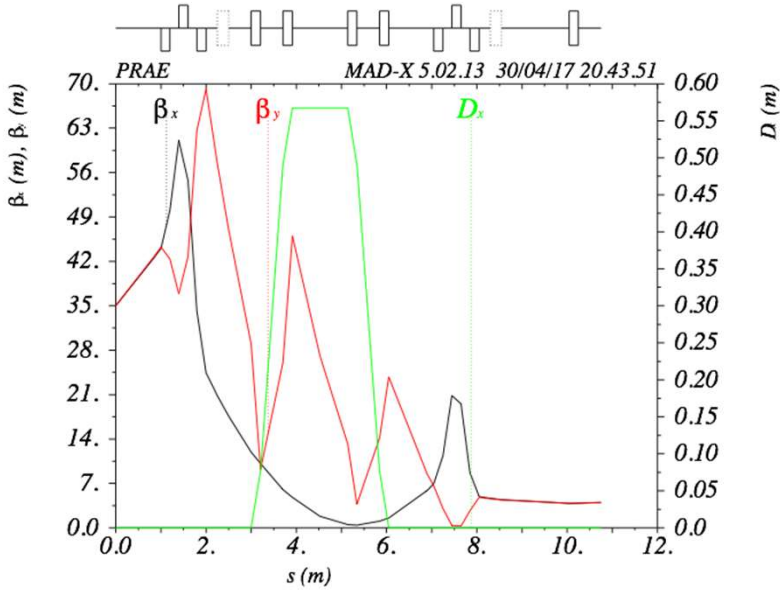
- **RF powering:**
  - Second generation SLAC modulator from S-band old 30 GeV linac being dismantled
  - The klystron characteristics has been identified

Accelerator: magnet and optics calculations

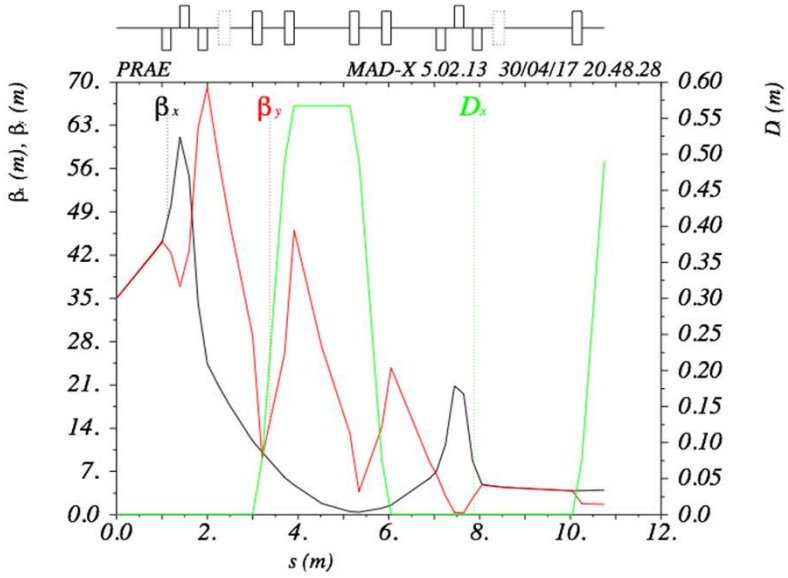
- **Design of the magnets** *(solenoid, dipole, quadrupole)* **ongoing**
- **Preliminary beam dynamics simulation:** done with ASTRA tracking code and RF-track
  → *additional focusing elements need to be applied*



- **Optics design and simulations**
  - Two triplets, flexible final conditions
  - with a Energy compression System (ECS) and a dedicated Beam Energy Measurement



Direct line: ProRad and Radiobiology



Deviated line: Instrumentation

Accelerator: progress summary

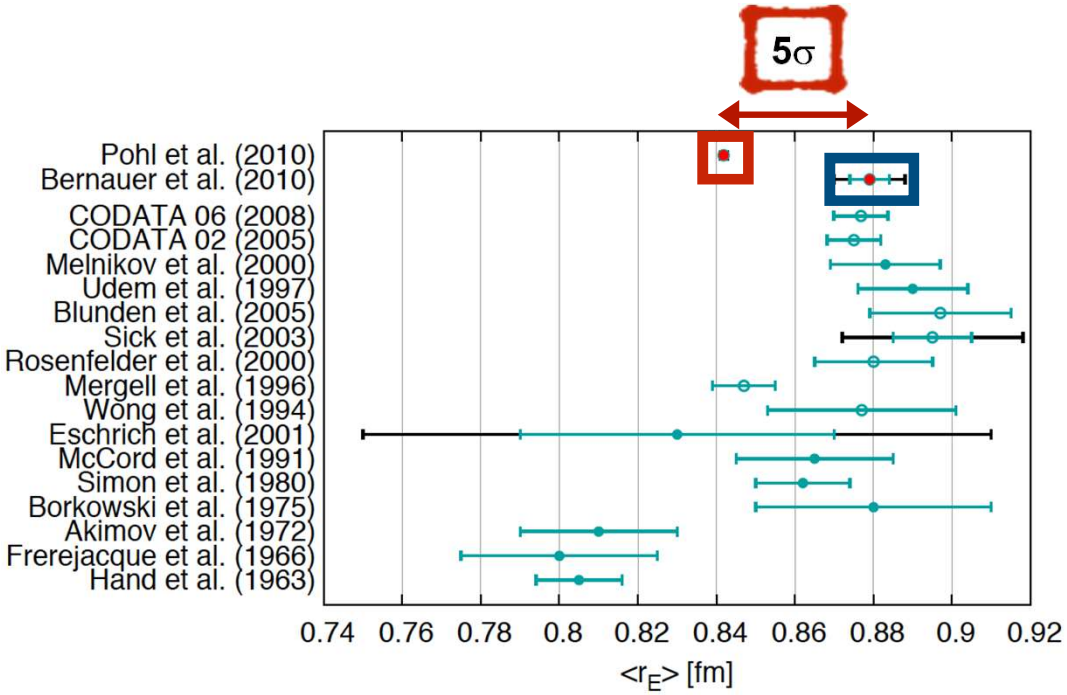
- **Beam dynamics simulations:**
  - Already **4 Master students** → *in part from French-Ukraine cooperation (LIA IDEATE)*
  - **Post-doc 2018/2019** *(exchange from radiobiology)*: beam calculation and implementation

- **Started the Beam Positionning Monitor tests** *(test bench at IPNO)*

- **Shift in the construction and expenses planning**
  - Order RF gun, klystron and linac RF early 2018
  - Visit at SLAC (december) to recuperate the accelerator's pieces

- **Communications PRAE and Accelerator:**
  - IPAC 2017: prooceeding on preliminary beam optics calculation and global project
    S. Barsuk *et al.* JACoW (2017) THPVA079
  - VHEE Radiotherapy 2017 *(Cockroft Institute, Daresbury)*: invitation, PRAE Accelerator & Medical
  - French-Ukrainian workshop *(LAL),* KINR and KIPT *(Ukraine, mars 2017)*
  - SFP 2017 : PRAE *(Roscoff)*

ProRad: the proton radius puzzle



Muonic hydrogen spectroscopy

r_p = 0.84184±0.00067 fm

Direct measurement

(10 times more precise)

$$r_p = \sqrt{< r^2 >} = \sqrt{-6 \frac{\partial G_E^2(Q^2)}{\partial Q^2}\Big|_{Q^2=0}}$$

Electron scattering experiments

r_p = 0.87900±0.00800 fm

Indirect measurement

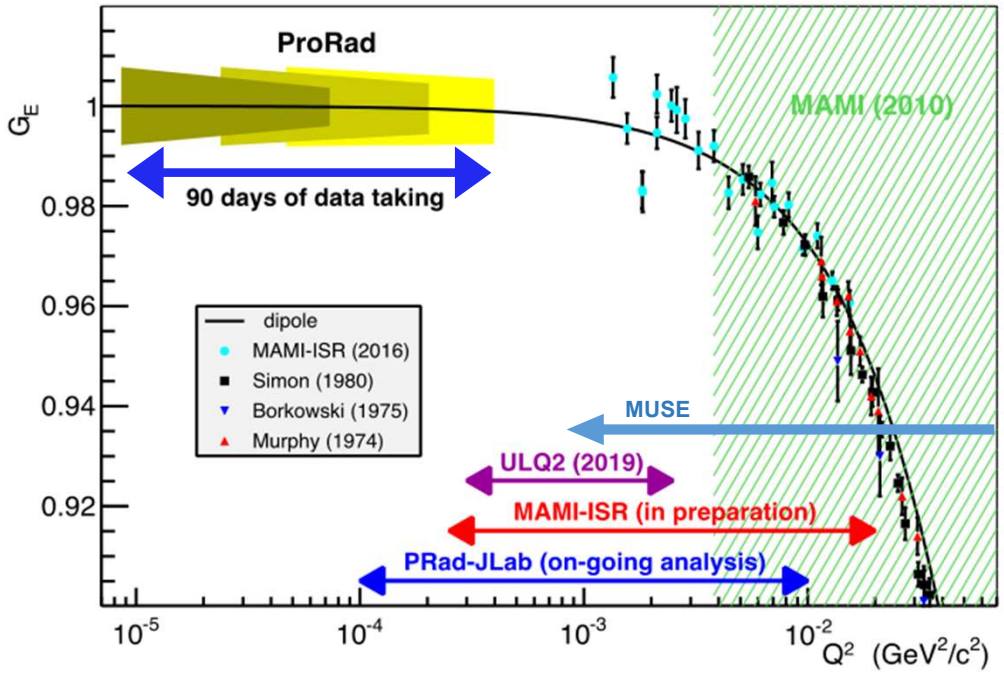
(extrapolation of Form Factor data to Q^2 =0)

→ **Problem**: the proton is smaller as « seen » by muons than by electrons

ProRad: the proton radius puzzle

Need for low Q^2 experimental electron scattering data

→ linear region in the form factor:
'Exact extrapolation'



ProRad goal: A high precision measurement of the proton electric form factor at very low Q^2

Foreseen results:

- **Better knowledge of the dependence of Form Factor on Q^2**
- **Significant impact on the measurement of the proton charge radius**

} **new physics?**

ProRad: experiment requirements

ProRad experiment requirements:

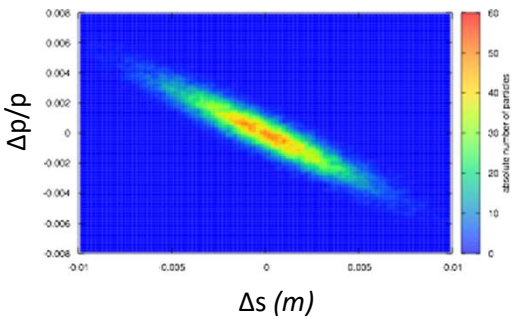
- High precision beam: **reduced energy dispersion** (**$5x10^{-4}$**)
- Precise knowledge of the **beam energy** (**$5x10^{-4}$**)

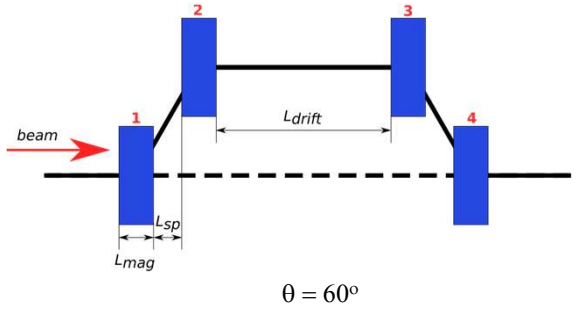
Beam energy compression system

→ A **chicane** of **4 identical dipoles** to reduce the phase space of the beam

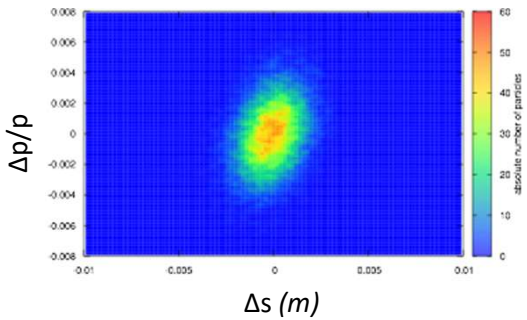
Association of a **RF** cavity to reduce by a **factor ~10**

Longitudinal phase space ($\sigma_{\Delta s} \approx 3$ *mm*)





Longitudinal phase space ($\sigma_{\Delta s} \approx 1$ *mm*)

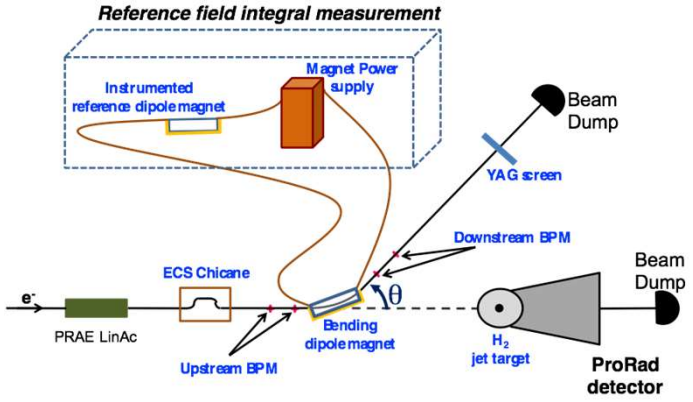


Beam energy measurement

→**Deviate** the beam in a **controlled magnetic field**: **absolute knowledge of the beam energy**

$$\delta E/E = 3 \times 10^{-4}$$

With a possible configuration of **1 m** long dipole with **0.5 T** field and a **60° deviation angle**



Reem Rasheed master thesis: IPNO and Lebanese University

ProRad: experiment requirements

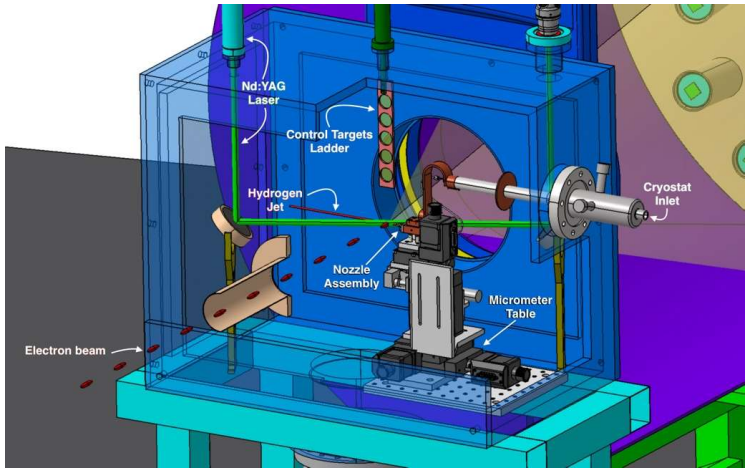
ProRad experiment requirements:

- High precision beam: **reduced energy dispersion** (**$5x10^{-4}$**)
- Precise knowledge of the **beam energy** (**$5x10^{-4}$**)
- A **stable hydrogen target**
- Optimized measurement of the **scattered electron energy** and **position**

French-German collaboration

hydrogen target

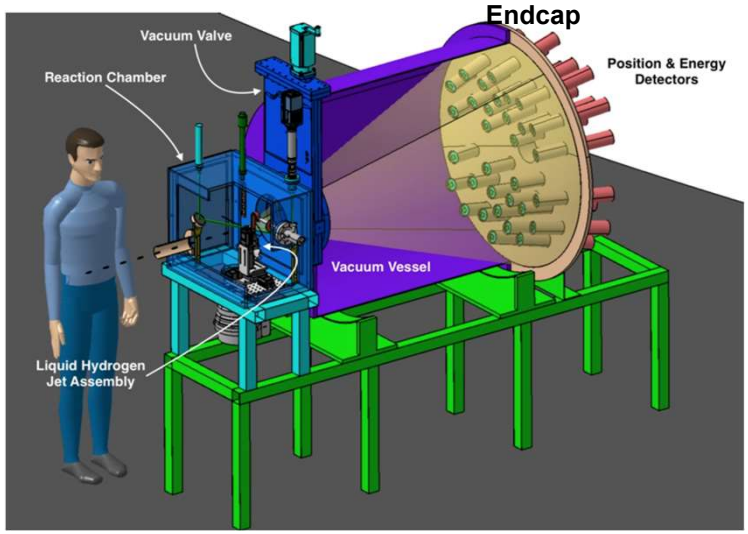
A very **stable windowless** and **self-replenishing** target of **15 µm diameter**



Ultra cold liquid technology developed at Frankfurt University

Reaction chamber with the target assembly

32 **elementary detectors** placed at **5** different **scattering angles** at a distance of **1.5 m** from the target



ProRad: progress summary

Experiment:

- **Detector conception** in a very elaborated phase *(full Geant4 simulation of the detector)*
- **Beam energy measurement technique** has been studied
- **Detectors** (BGO crystals) are under tests → order of all crystals early 2018
- **Hydrogen target** was part of an ANR proposal with the Frankfurt Univ. *(final round but not selected)*.
  - A solution to secure the target construction within the current budget limits is studied.
  - Enlargement of the collaboration for the construction of the position detector is considered.
  - Submission of a new proposal to DFG/ANR…

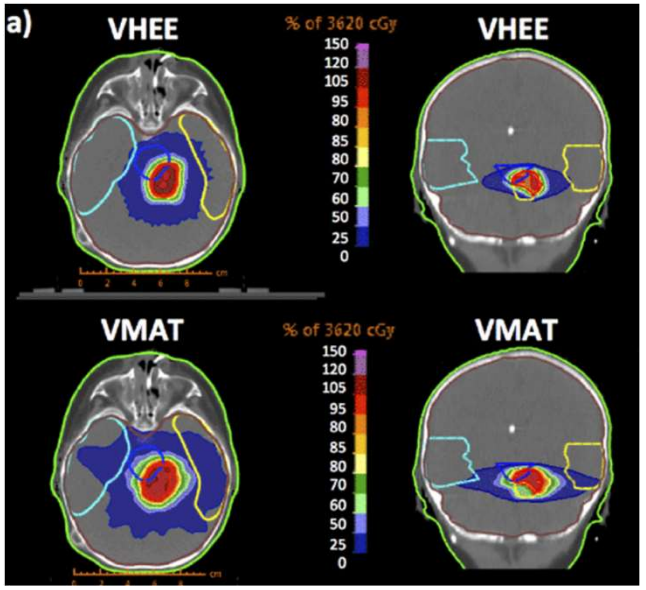
Training, communication, Collaboration:

- Already **3 master students** on ProRad , **1 postdoc** *(started 6 month ago)*
- ProRad@PRAE has been presented at several conferences and workshops:
  - SFP 2017 in Orsay in July
  - EINN2017 in Paphos, Cyprus in November 2017
  - French-Ukrainian workshop at LAL in Novembre 2017
- Extended collab: The GWU of Washington, the JGU of Frankfurt, and the LPC of Caen joined the ProRad team

Advantage of VHEE beams for Radiotherapy

VHEE beams: advantages vs MV photons

- ✓ ***Very good dosimetric properties*** **:** low-lateral penumbra, flat longitudinal profile, no perturbation at heterogeneity interfaces
- ✓ ***Magnetic collimation***: pencil beam scanning, precise intensity modulated irradiations *(DesRosiers et al., Indiana)*



Brain tumour dose maps for 100 MeV VHEE and 6 MV volumetric modulated arc photon therapy (VMAT) *Bazalova-Carter, 2015*

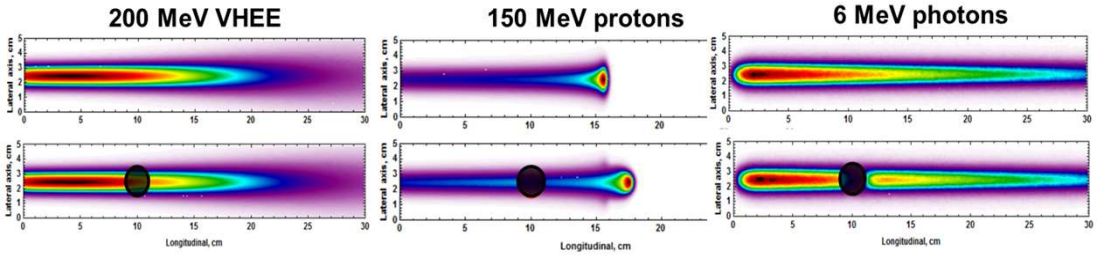
Clinical cases comparison *:*

Better organ-at-risk protection with VHEE compared to VMAT *(Bazalova-Carter et al., Stanford)*

VHEE beams: advantages vs protons

- ✓ ***Cost :*** more compact accelerators
- ✓ ***Easier beam manipulation***

→ No biological experiments *in vitro* or *in vivo*

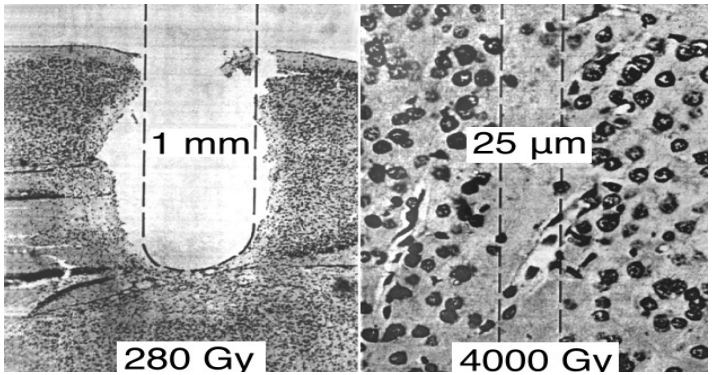


Behavior of VHEE, photon and proton beams traversing a air cavity *(Agnese Lagzda, manchester)*

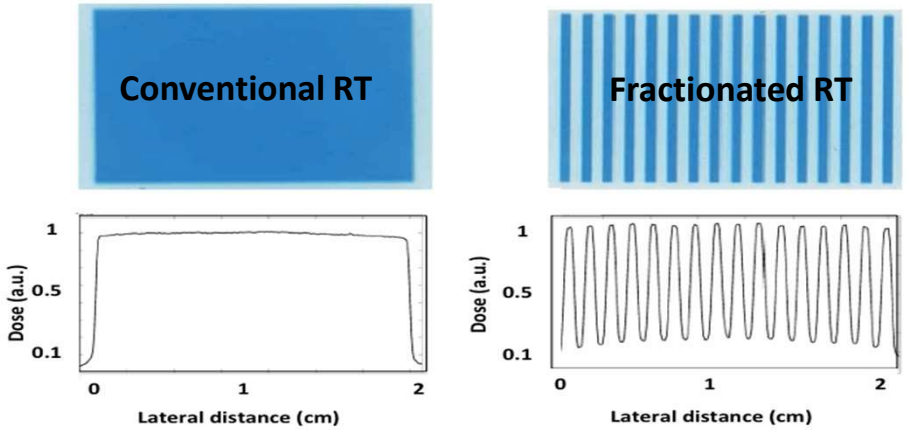
Radiobiology: spatial fractionation of dose

Spatial fractionation of dose and minibeam radiation therapy (MBRT):

Very small field size (< 1 mm^2) + Spatial fractionation of dose

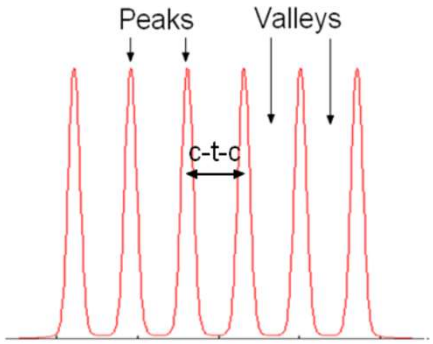


Zeman et al., Science (1959)



→ **Dose-volume effect**: the smaller the beam size, the higher the tolerance of healthy tissues

IMNC → Rat brain tolerance increased up to **100 Gy with MBRT** *(Prezado et al.)* when conventional RT is limited at 20 Gy



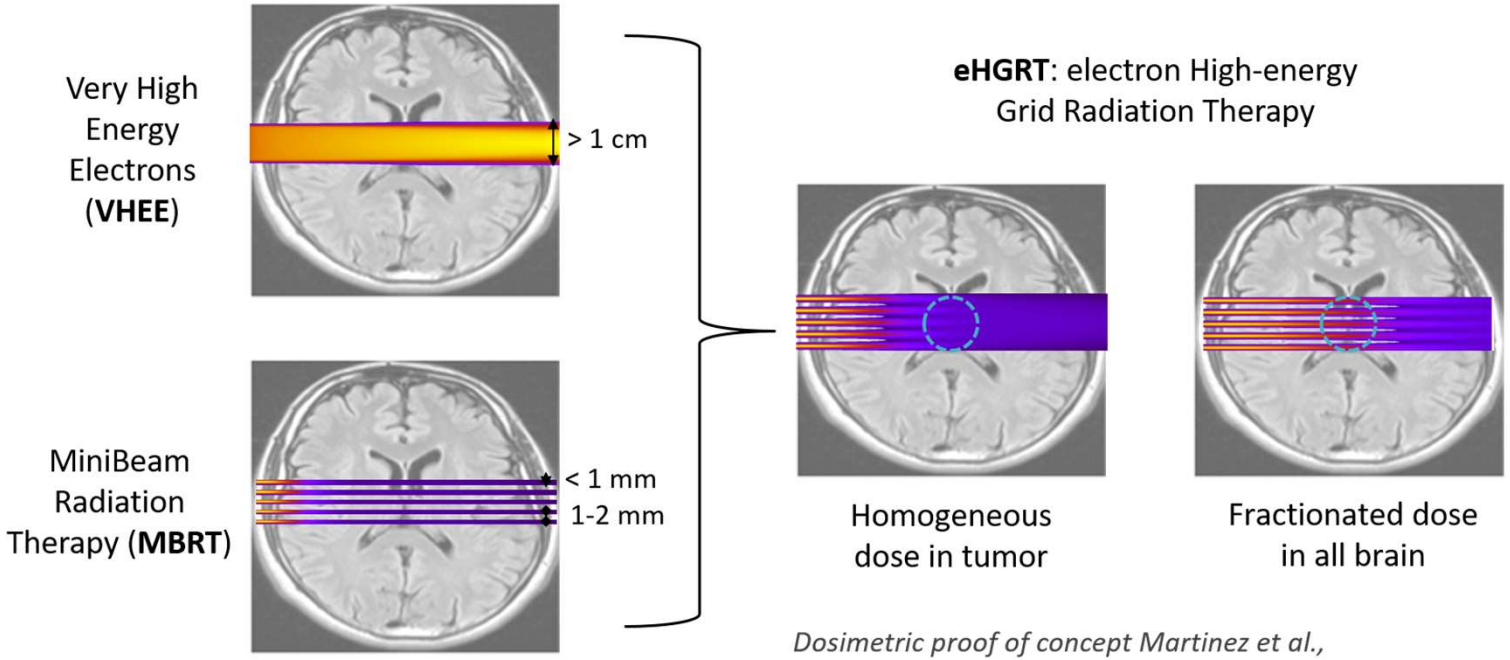
$$PVDR = \frac{D_{peak}}{D_{valley}}$$

↗ *PVDR* = ↗ *tolerance to healthy tissues*

Grid therapy with VHEE beams < 1 cm ?

Radiobiology: eHGRT

Objectives of IMNC@PRAE: combine advantage of VHEE beams with spatial fractionation

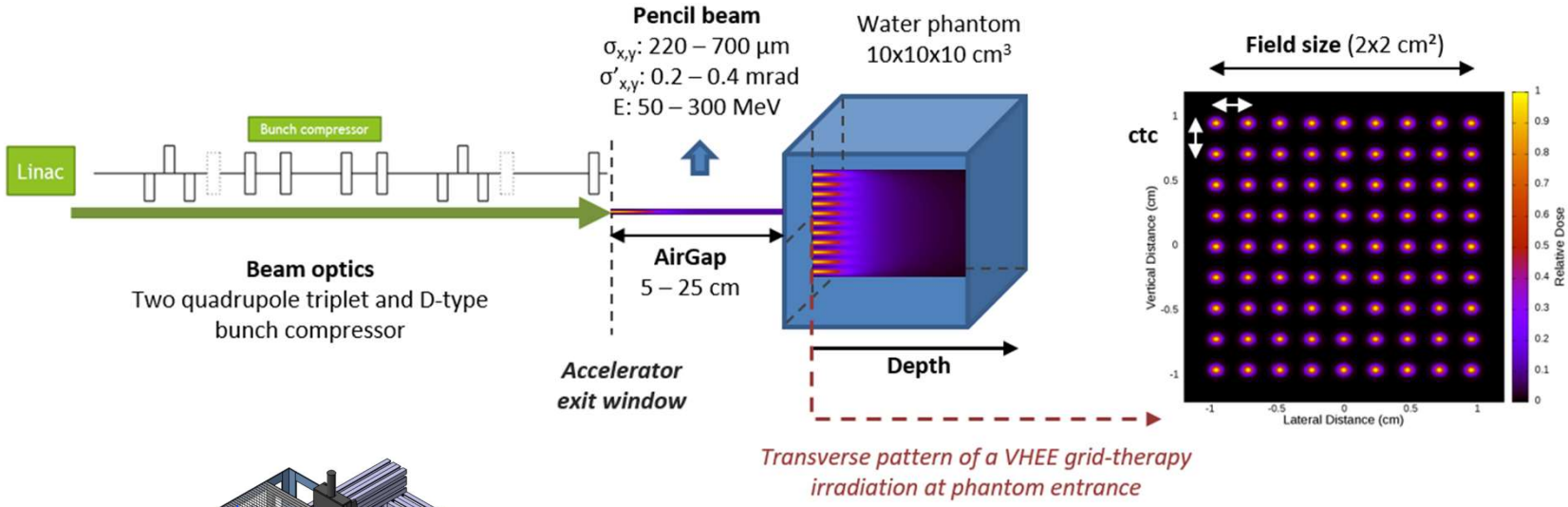


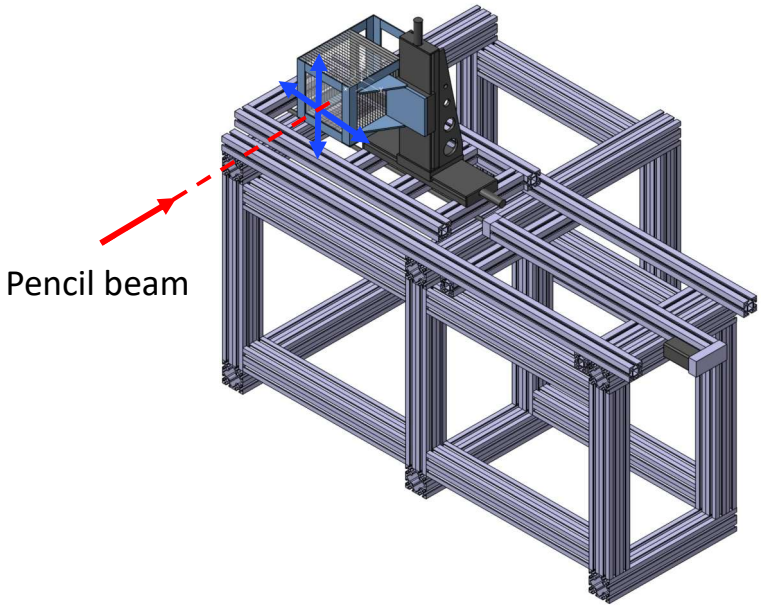
Dosimetric proof of concept Martinez et al., Med. Phys. 2015

→ **At PRAE**: perform all the numerical and experimental dosimetric validation until the *in vivo* proof of concept

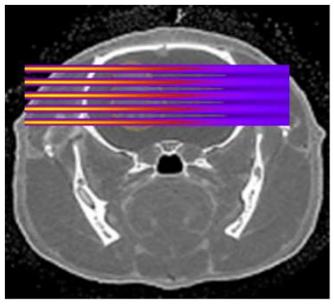
Radiobiology: preliminary results

Beam-optics calculations for preclinical experiments :

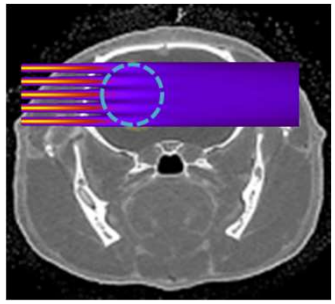




Work in progress in rat-head CT images:

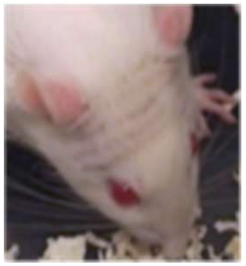


140 MeV, σ 250 µm
Optimization of tissue sparing



70 MeV, σ 350 µm
Tumor control optimization

Radiobiology: progress summary



- **Monte Carlo studies**:
  - Beam optics optimization: dosimetry in water *(finished)*
  - Preclinical calculations in progress

- **Experiments** *(year 2020 - 20…)*:
  - **Experimental dosimetry**: challenge of VHEE and very small beam sizes
  - **In vivo proof of concept**: efficiency of eHGRT for high-dose **healthy-tissue tolerance**

→ ***In vivo* experiment would be a specificity of PRAE / other VHEE installations**

- **Infrastructure needs**:
  - Allowing animal experiments on the prae site: preparation room close to beam line, isolated area for decontamination and non-intrusion, air-extraction…
  - Need for comprehensive study and additionnal budget → support from expertise and animal facility of Institut Curie…

- **Interest of the PRAE beam** for other radiobiological experiments: « Flash-effect »

- Participation to Congress: « VHEE radiotherapy » *(2017, Daresbury)* and next ESTRO conf. *(2018, Barcelona)*

Instrumental Platform: reminder

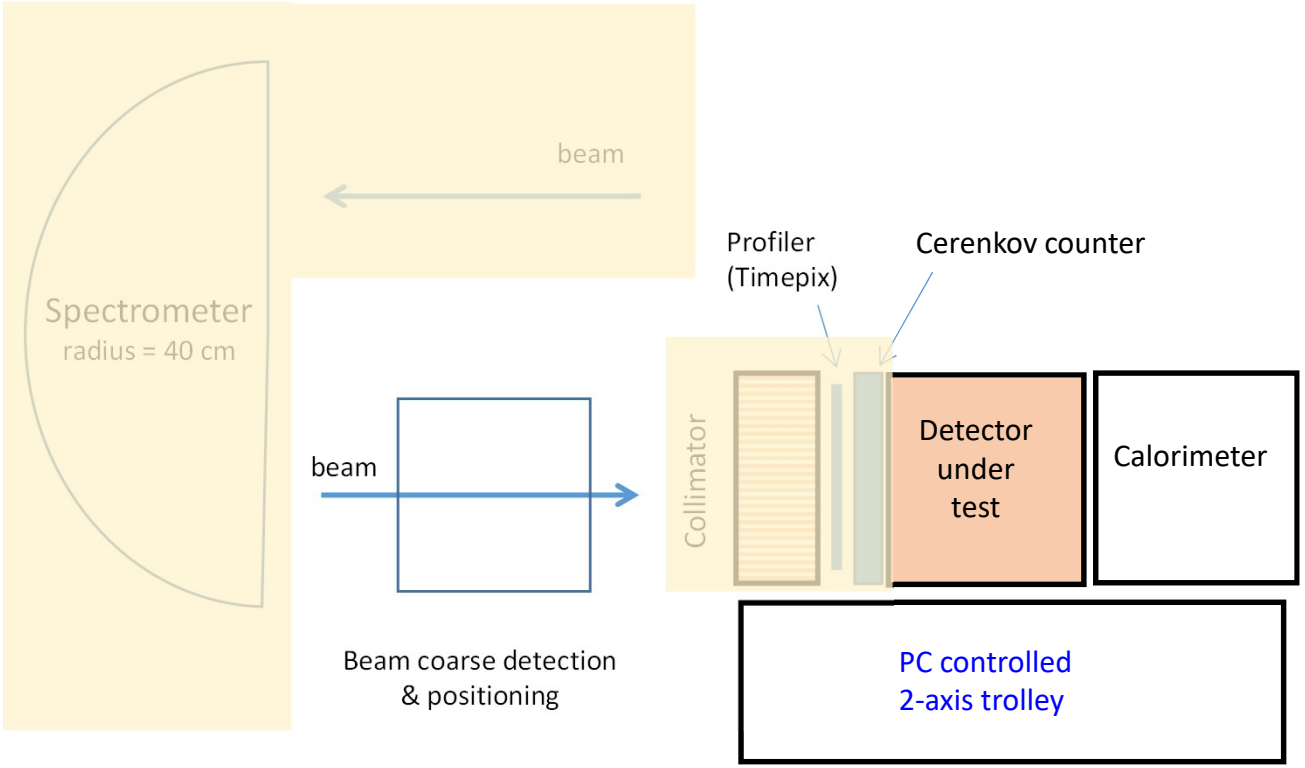
- **Provide a test platform for detectors based on a pulsed electron beam**
- **User cases: calibration for particle & nuclear physics detectors, medical imaging**

  - Excellent technical performance
    - Timing reference (<10-ps bunch width)
    - Charge accuracy (< 2×10^{-3} RMS)
    - Low straggling (high energy)

  - High-performance, remotely controlled tools for R&D →rapid and convenient set up
    - Beam positioning and profiling
    - Cherenkov quartz counter for Intensity monitoring
    - Calorimeter for Energy monitoring
    - 30 digitization channels with the WaveCatcher digization system on a NARVAL-based data acquisition
    - motorized table for scanning (<500-µm accuracy)

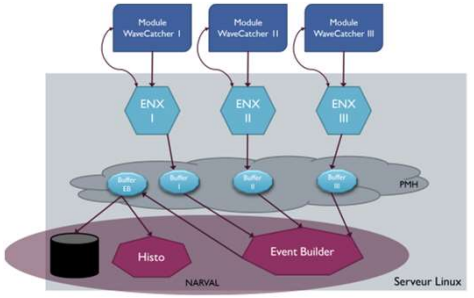
  - No need to place the detectors in vacuum

Instrumental Platform: phase 1



DAQ + slow control

- 32 digitization signals (WaveCatcher) for the user
- DCOD = NARVAL + ENX
- Possible online signal processing

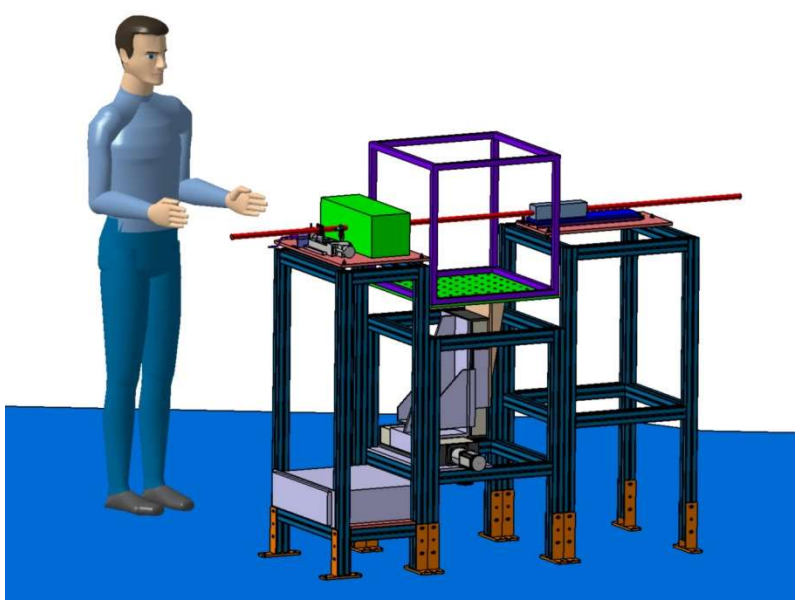


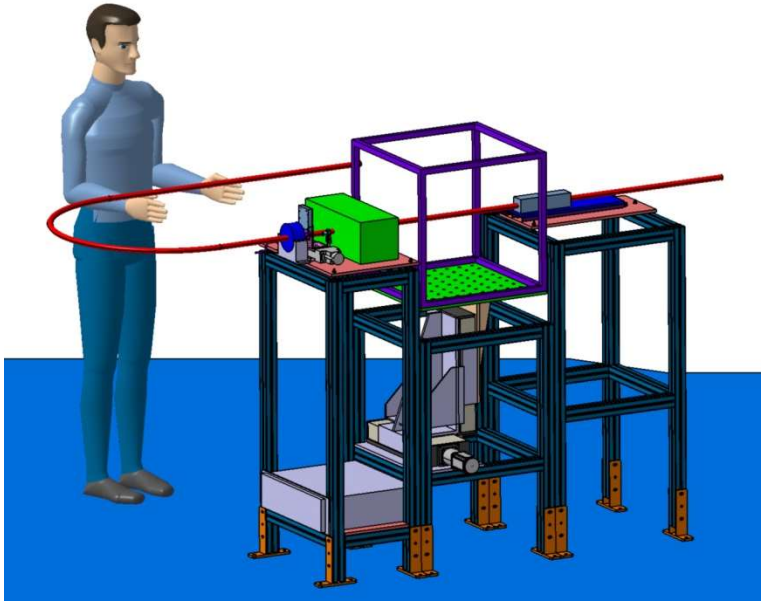
→ Benefit for ProRad detector tests

User-Friendly interface/programs for control and analysis

Instrumental Platform: Progress summary

- Shifts due to the funding situation
- « Phase 1 » : no spectrometer (75 k€) → no TimePix (10 k€)
- Mutualize purchases
  - Scan motor with radiotherapy requirements
  - 1 cristal tested for ProRad → calorimeter
  - Share ProRad equipment (supplies, PMT, DAQ)

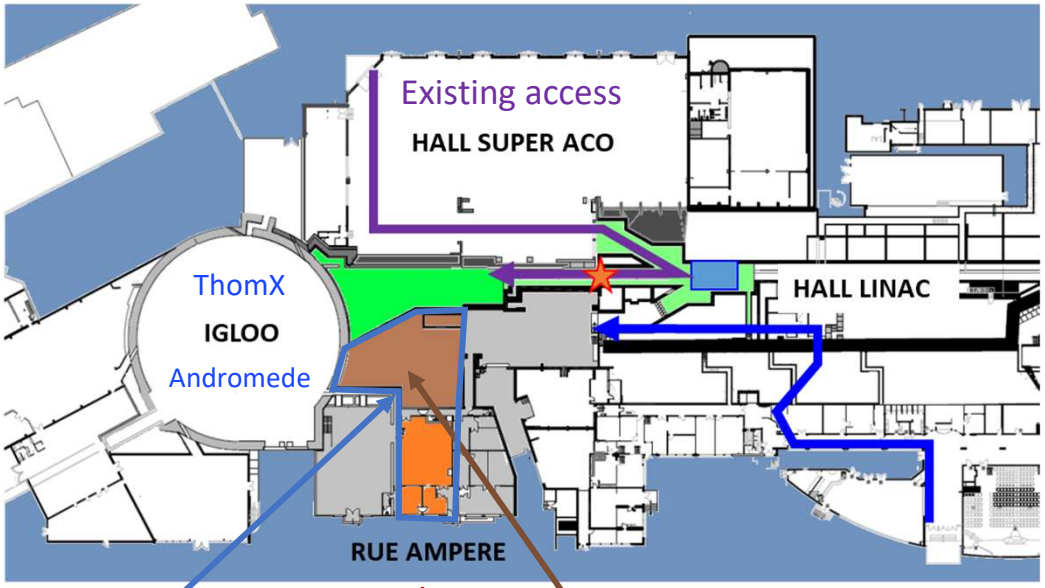




Infrastructure: where are we?

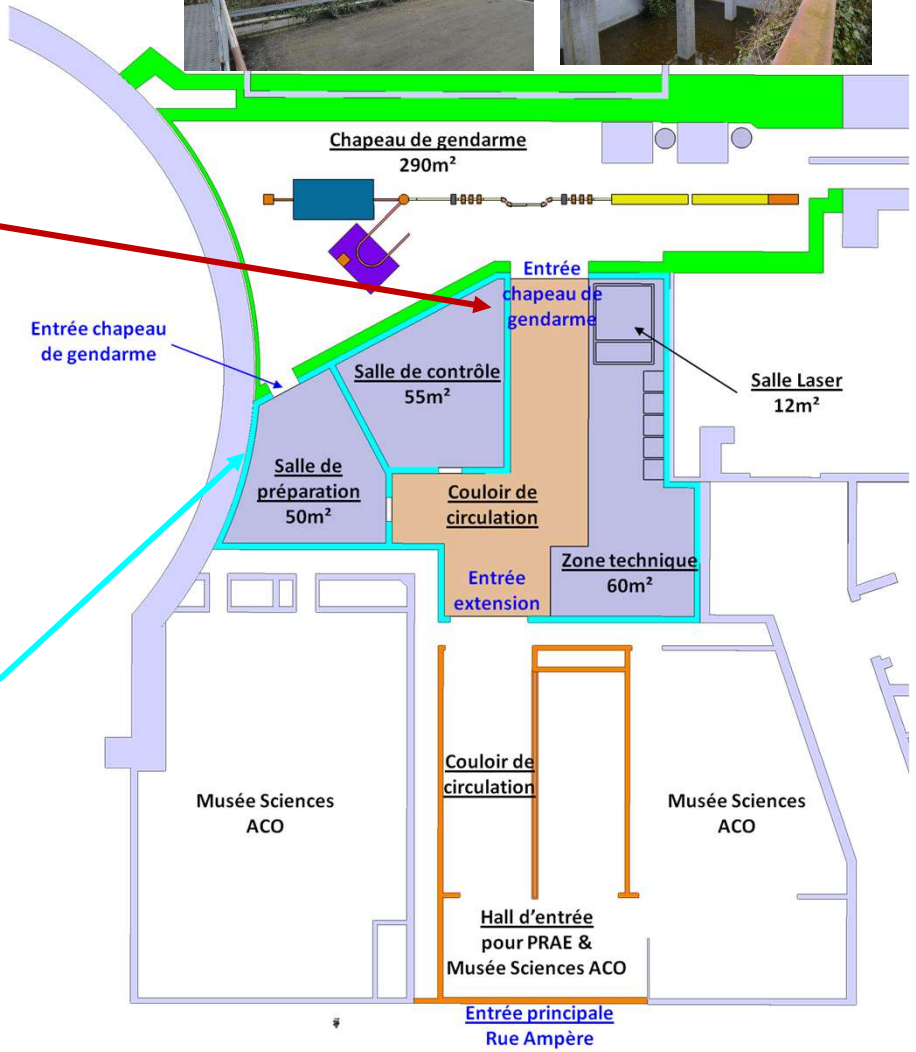
- **Existing structure, some Issues:**
  - Locked and radioprotected site, no practical access
  - No actual technical infrastructures
  - Building conditions (water infiltrations)

- **Objectives**:
  - Creating an **practical access**
  - Meeting the **needs of scientists** *(direct access for the radiobiology)*
  - Have a **pooled installation**
  - Platform for annex equipment
  - Renovation of the roof



Infrastructure: New version

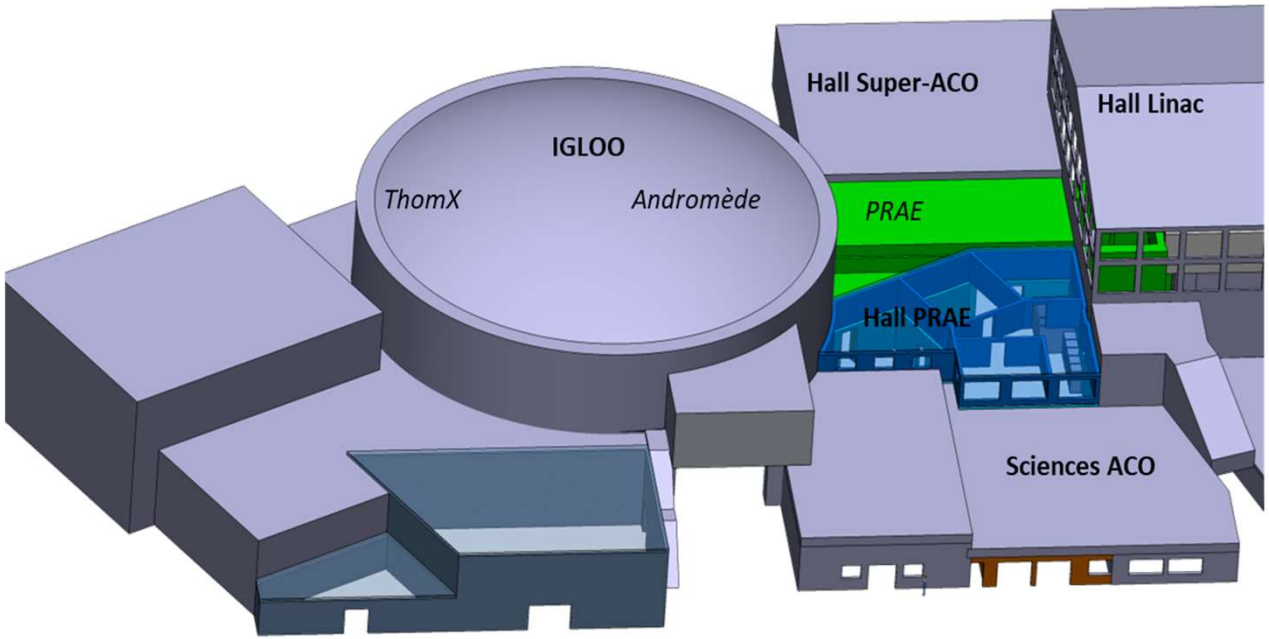
- **Preliminary work before extension construction:**
  - Earthwork, land withdrawal, renovation of roof and walls
  - Creating openings on the north façade, Removal of concrete blocks…



- **Construction of an extension (max : 290 m²) :**
  - Ground level : control room, biological preparation room, laser, technical zone…
  - First level: option
  - Roof : ventilation and cold cabinet

Infrastructure: progress summary

- **Work programming:**
  - Reception of topographic and altimetric surveys *(sept. 2017, Progexial)*
  - **Specifications for a programming study** of the works submitted to the Paris-Sud University *(awaiting return)*
  - Upcoming: **tender for earthworks** followed by the Heritage Department of Paris Sud University
  - Upcoming: start of **radiation protection** studies



Budget

- **Fundings**:

Equipment

P2IO		514 k€
SESAME		1070 k€
LAL/IPNO		100 k€
TOTAL :		**1684 k€**

+ Infrastructure → CPER

2 post-docs (P2IO/in2p3)

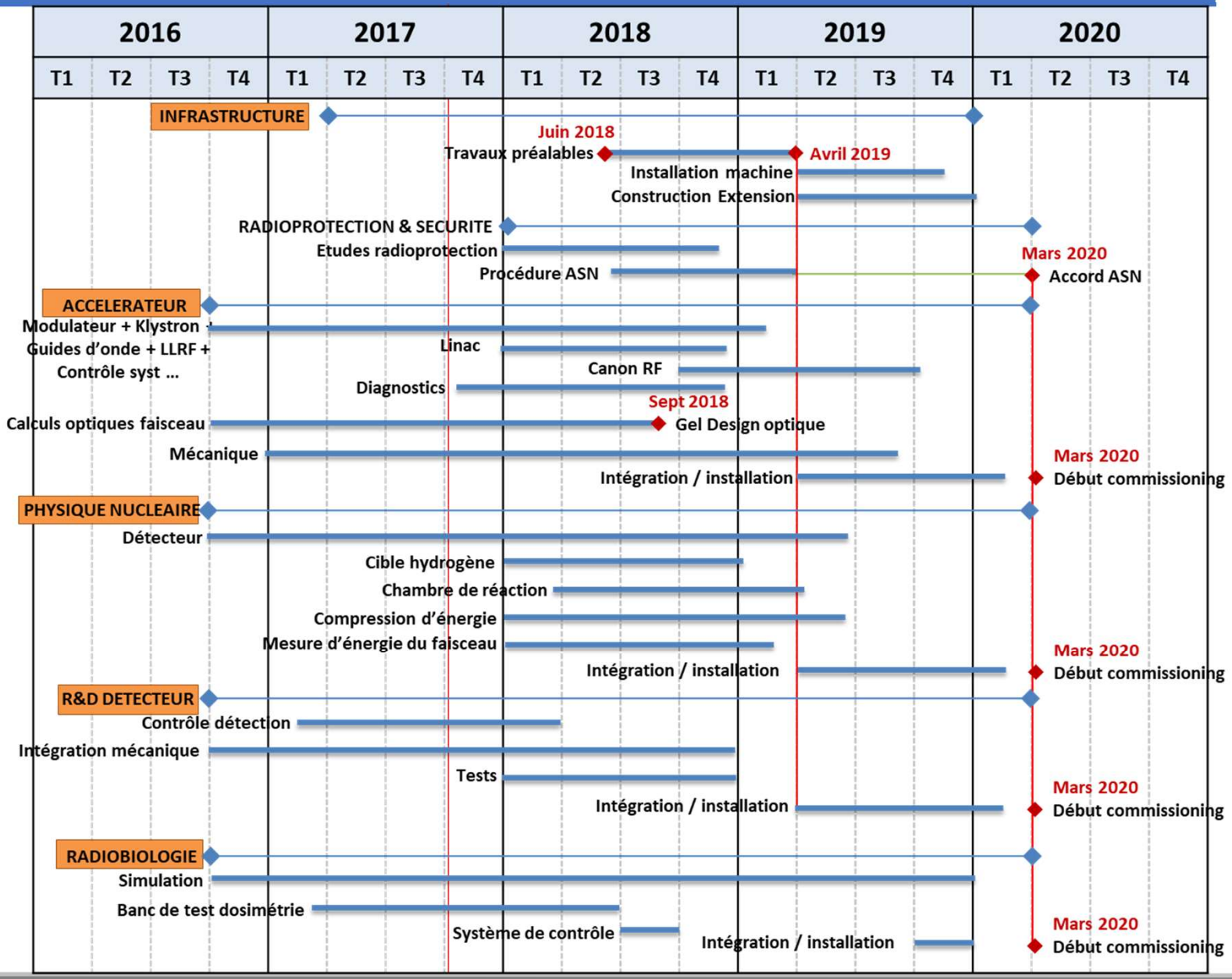
- **PRAE cost: Phase 1**

→Machine with recovered and shared equipments = **2161 k€**
(Laser PHIL, SLAC elements as modulators, BPM, wave guide…)

→ **477 k€ missing**, research for other budget and collaboration

- Planned expenses on 2017-2018 funded *(shifted)*

Planning


2016
2017
2018
2019
2020
T1 T2 T3 T4 T1 T2 T3 T4 T1 T2 T3 T4 T1 T2 T3 T4 T1 T2 T3 T4
INFRASTRUCTURE
Juin 2018
Travaux préalables
Avril 2019
Installation machine
Construction Extension
RADIOPROTECTION & SECURITE
Etudes radioprotection
Procédure ASN
Mars 2020
Accord ASN
ACCELERATEUR
Modulateur + Klystron
Guides d'onde + LLRF +
Contrôle syst ...
Linac
Canon RF
Diagnostics
Sept 2018
Calculs optiques faisceau
Gel Design optique
Mécanique
Intégration / installation
Mars 2020
Début commissioning
PHYSIQUE NUCLEAIRE
Détecteur
Cible hydrogène
Chambre de réaction
Compression d'énergie
Mesure d'énergie du faisceau
Intégration / installation
Mars 2020
Début commissioning
R&D DETECTEUR
Contrôle détection
Intégration mécanique
Tests
Intégration / installation
Mars 2020
Début commissioning
RADIOBIOLOGIE
Simulation
Banc de test dosimétrie
Système de contrôle
Intégration / installation
Mars 2020
Début commissioning

Conclusion

- **Advances in the four axes:** budget optimization, equipment sharing
  - Simulation work: beam requirements for experiments, magnets, detector & table design…
  - Accelerator: a postdoctorant will start in 2018
  - Infrastructure: proposal for an extension of the building
- **Training, communication, collaboration**:
  - 6 Master students *(2-4months)*, 2 postdocs
  - Presented in a dozen of conferences *(2 reference proceedings)*
  - Extended collaborations: Caen, Frankfurt, Washington *(ProRad),* Institut Curie *(Radiobiology)*
- **Project monitoring**:
  - 10 meeting/y with WP responsible, 4/y with steering committee *(laboratory directors)*
  - Scientific Councils of LAL and IPNO

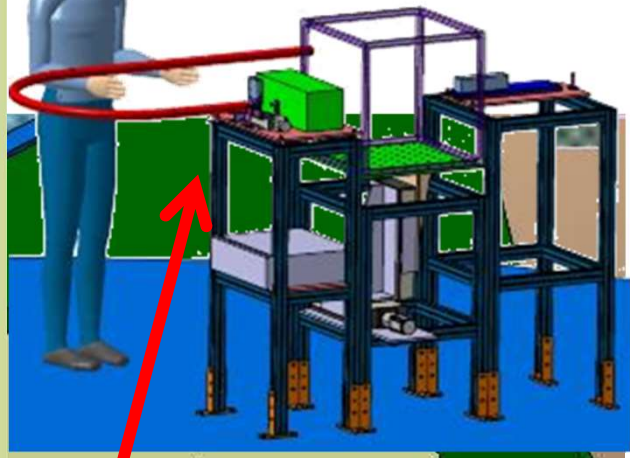
References:

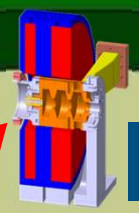
1. Marchand D. et al. *A new platform for research and applications with electrons: the PRAE project*. EPJ Web Conf. 2017;138:1012. doi:10.1051/epjconf/201713801012.
2. Barsuk S et al. *First Optics Design And Beam Performance Simulation Of Prae: Platform For Research And Applications With Electrons At Orsay*. In: IPAC 2017, Copenhagen, Denmark. ; 2017.

PRAE in one slide - Thank you

Energy compressor

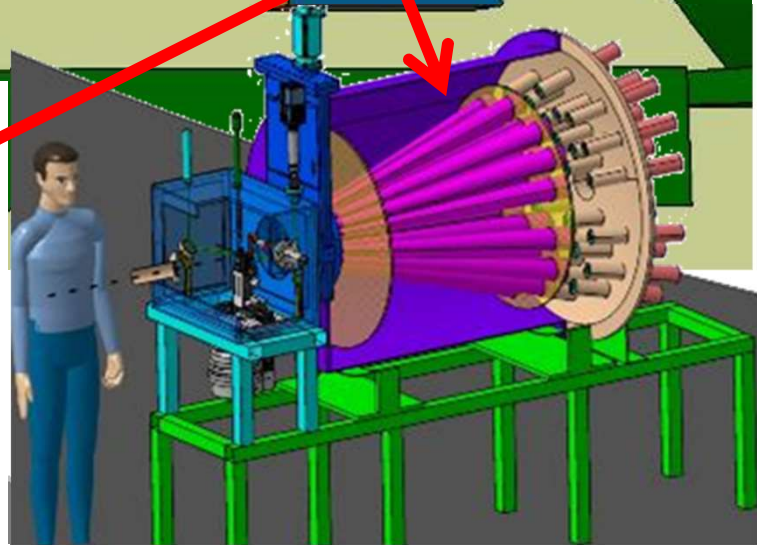
Instrumentation



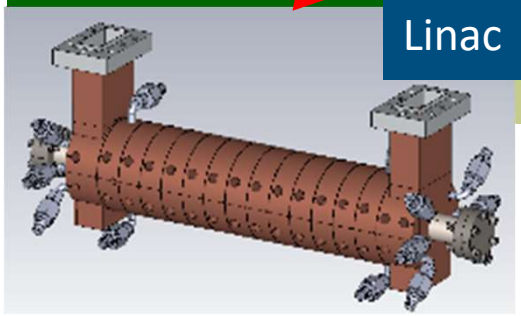


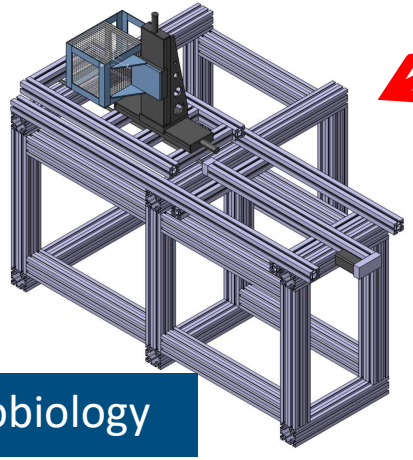
RFgun

ProRad



Linac





Radiobiology