P2IO Scientific Council 23-24 November 2017: status report on

PRAE

Platform for Research and Applications with Electrons

Mostafa HOBALLAH on behalf of the **PRAE collaboration**

60+ members

Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3, Universités Paris-Sud & Paris-Saclay

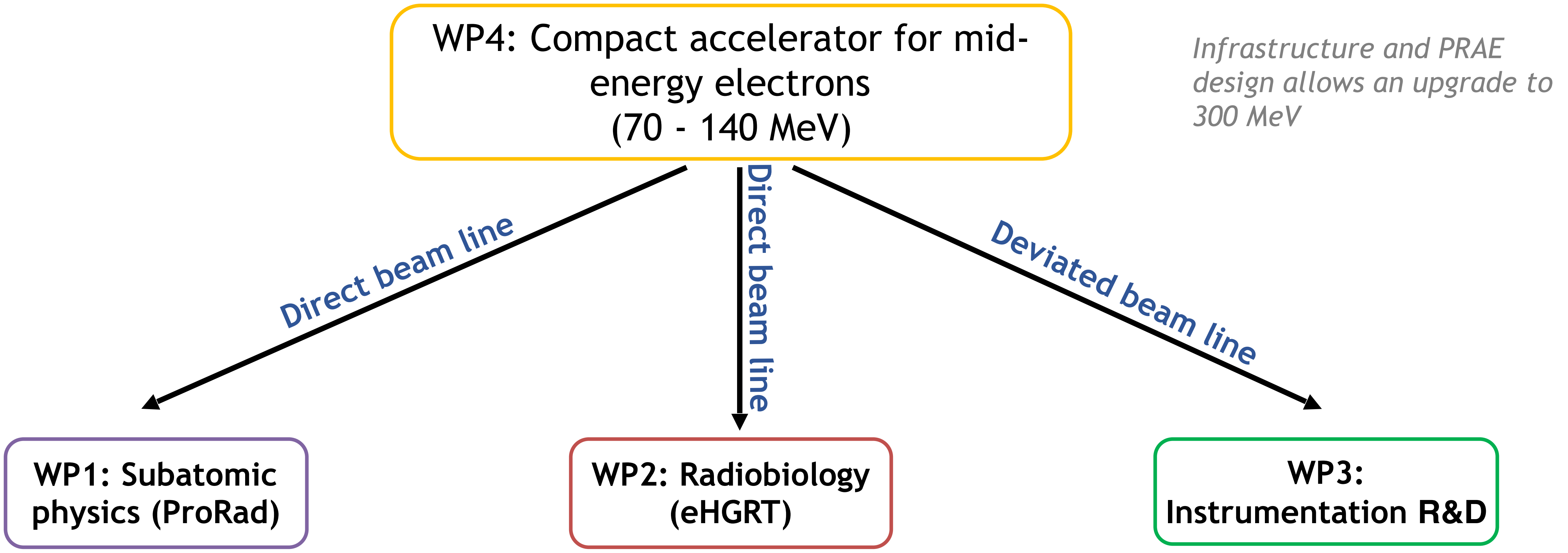
Member laboratories

Funding agencies

What is PRAE?

Physics goals and Work Packages

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



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

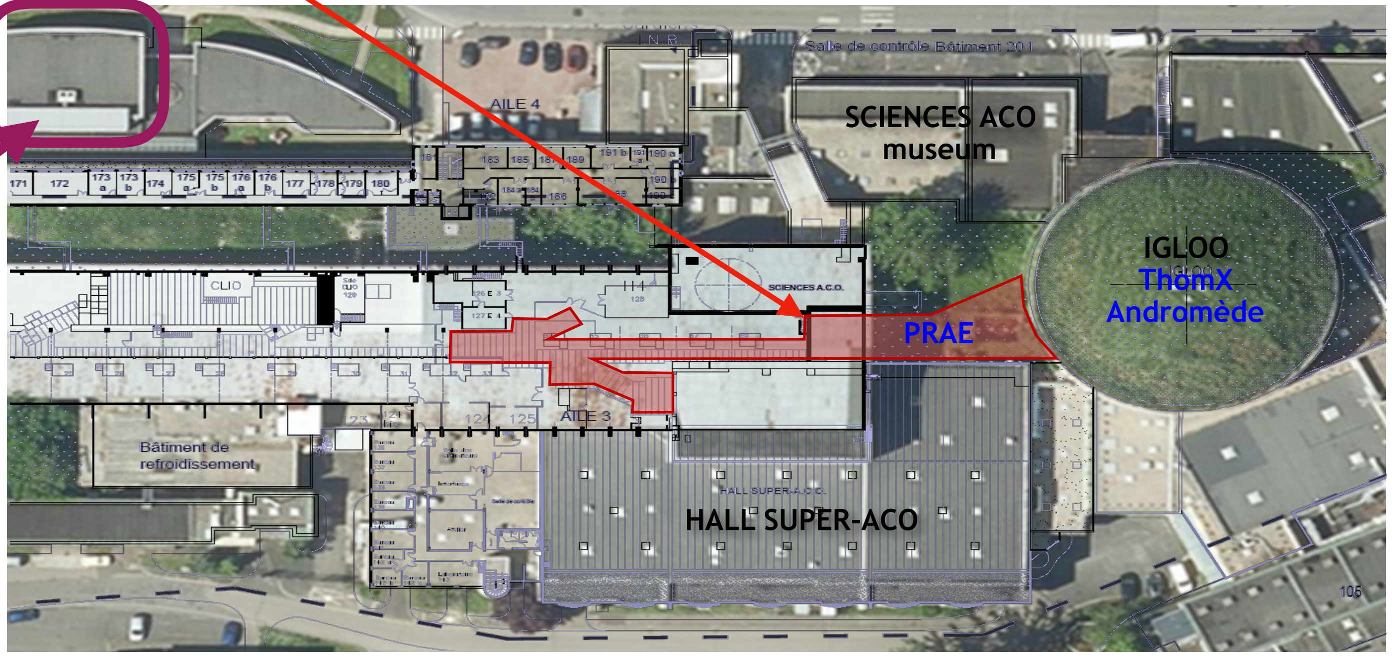
WP4: construction of the machine for the WPs required beam performance

Organisation

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

We are in this auditorium



Organization:

Project Coordinator
Sergey Barsuk

Technical Coordinator
Patricia Duchesne

- WP1: **Nuclear Physics** (IPNO) — **Eric Voutier**
- WP2: **Radiobiology** (IMNC, IPNO, LAL) — **Y. Prezado** (R.Delorme)
- WP3: **Detector R&D** (LAL, IPNO, IMNC) — **Bernard Genolini**
- WP4: **Accelerator and beam instrumentation R&D** (LAL, IPNO) — **Angeles Faus-Golfe**

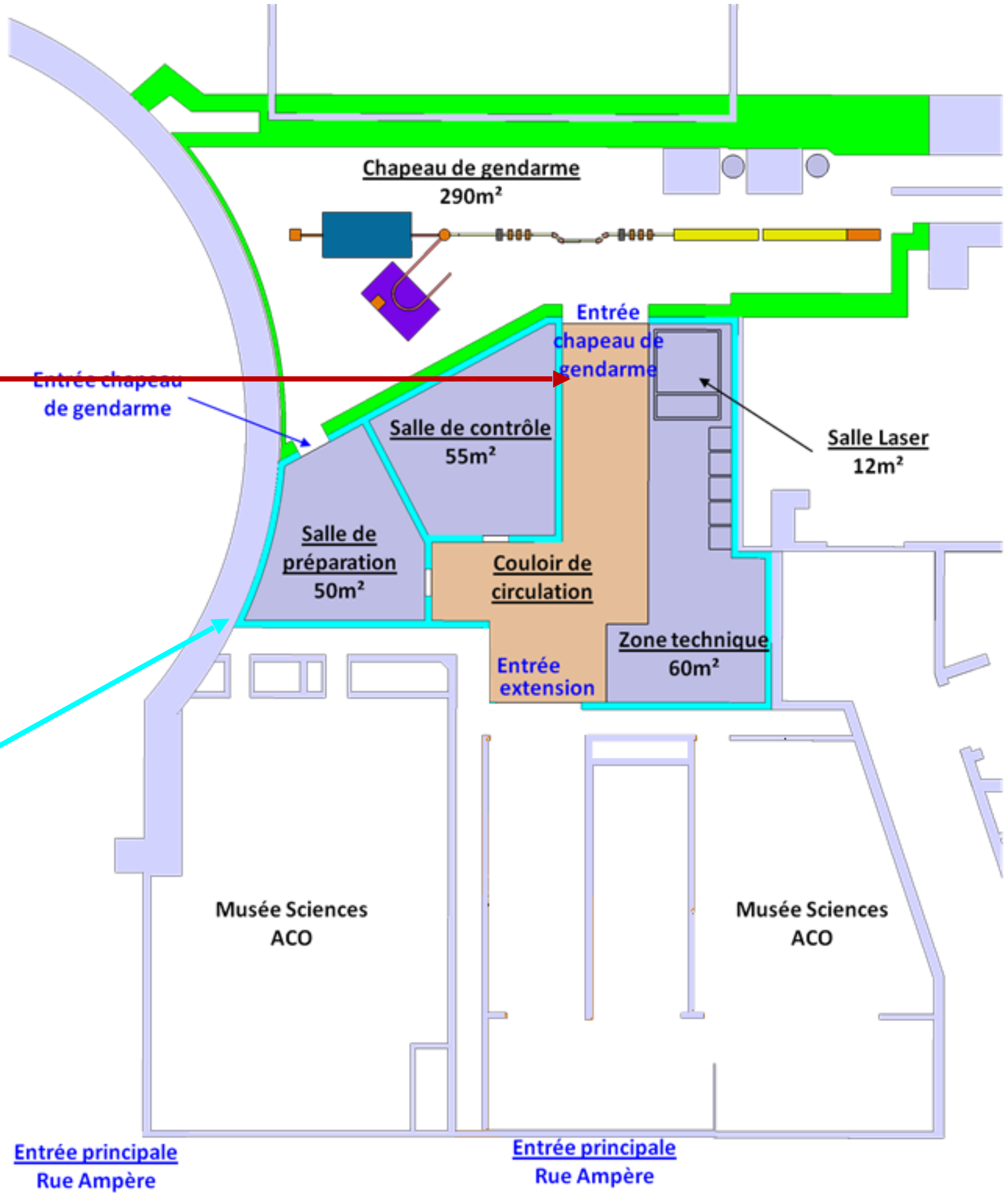
PRAE Infrastructure

Revised version

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

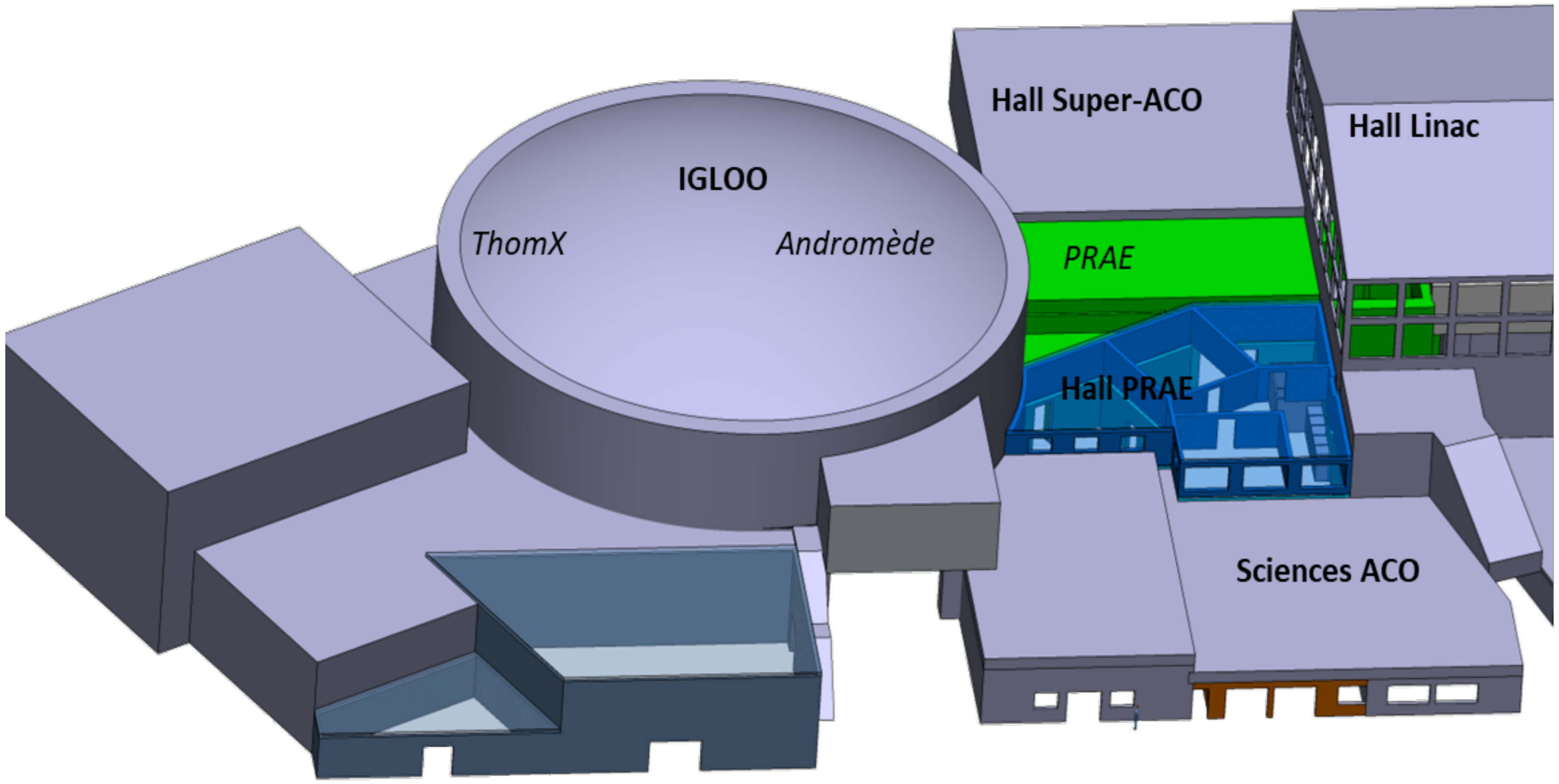
- **Preliminary work before extension construction:**
  - Earthwork, land withdrawal, renovation of roof and walls
  - Creating openings on the north wall, Removal of concrete blocks…

- **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

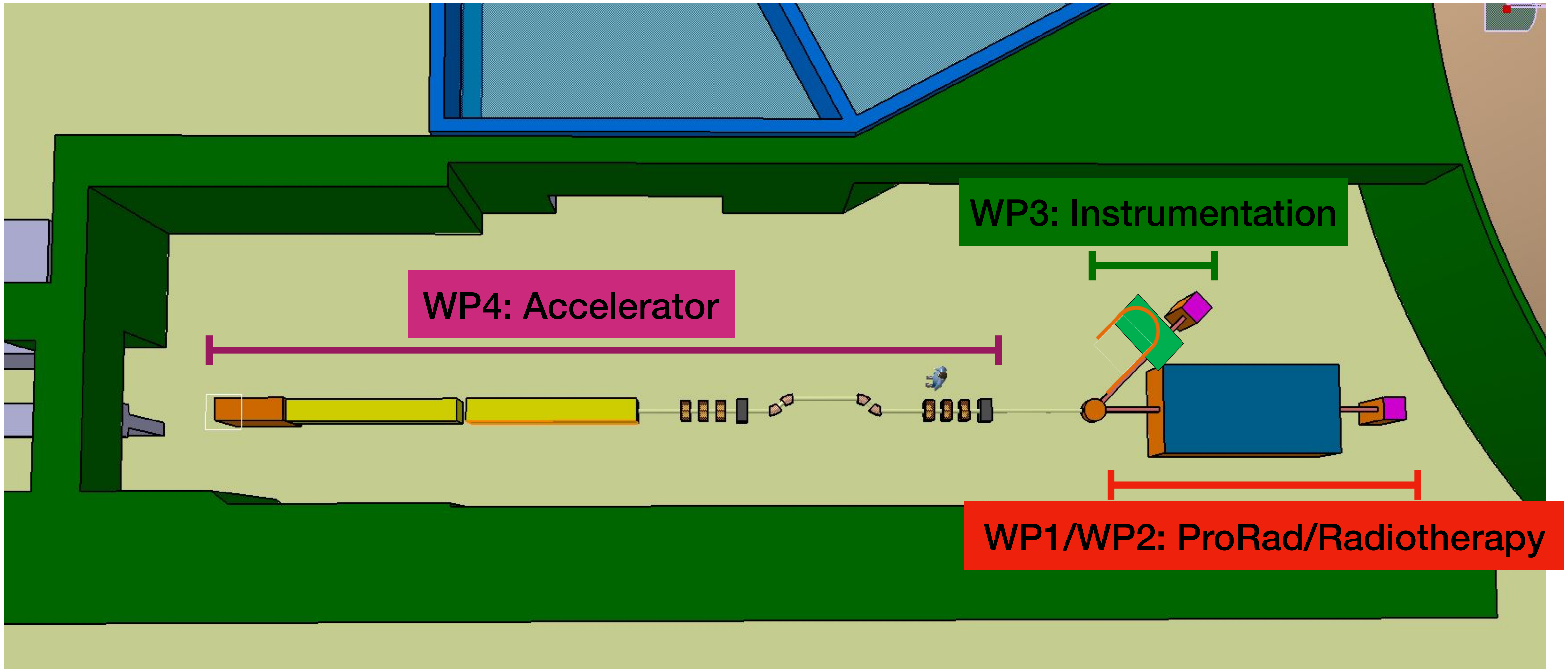


Progress summary

➢ **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



PRAE Work Packages

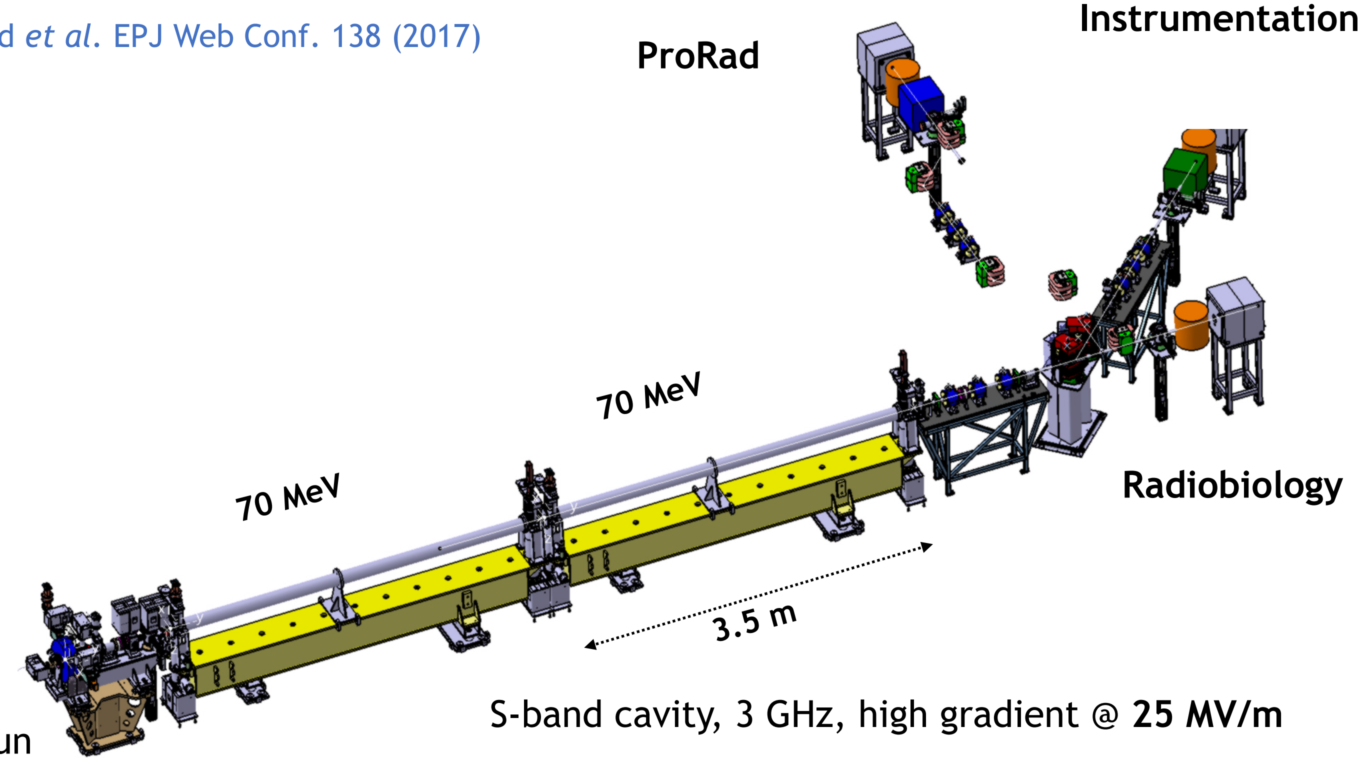


Evolution of line design

Initial version: 3 beam lines

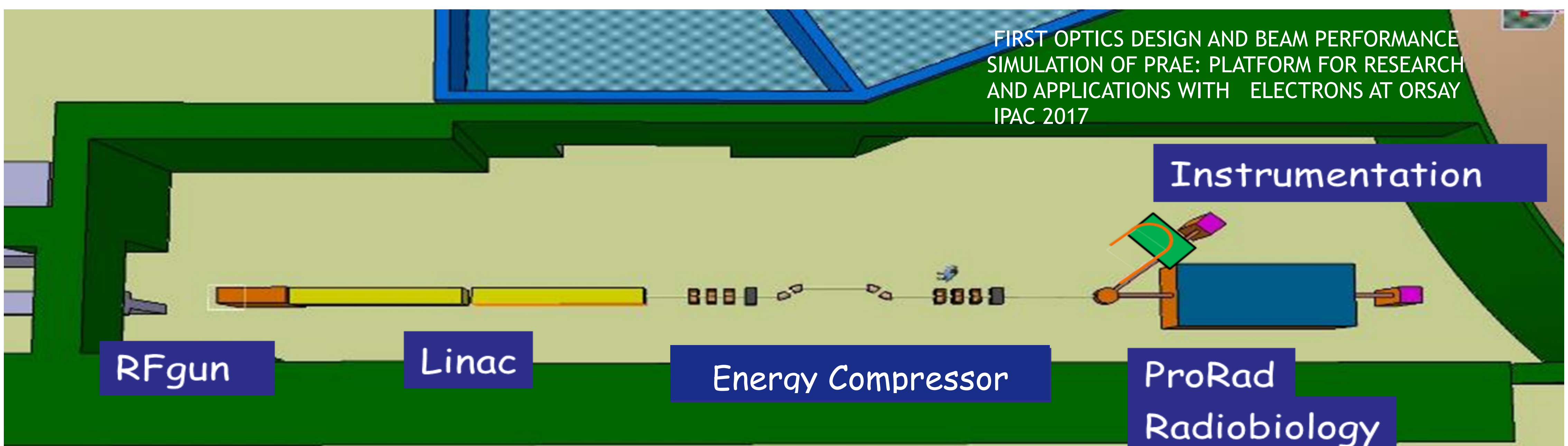
D. Marchand *et al.* EPJ Web Conf. 138 (2017)

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



Currently:

- Optimised version: ProRad and Radiobiology on the direct line

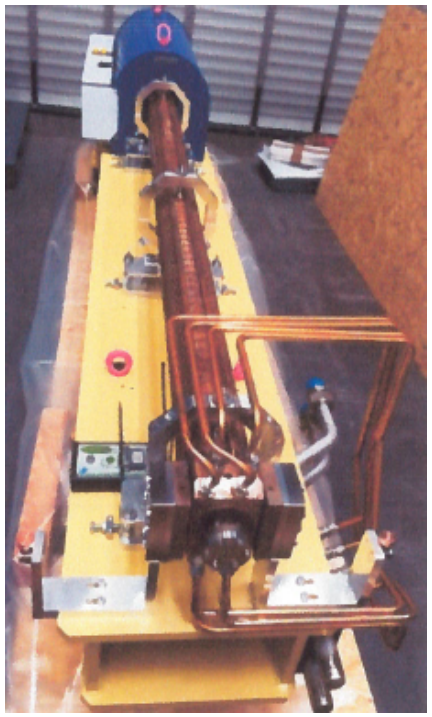


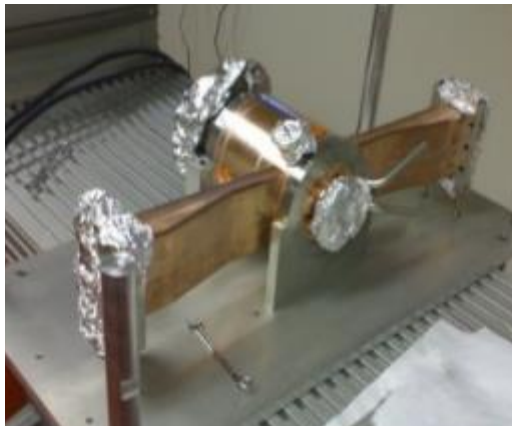
RF gun and Linac

- **The RF:**
  - Initially: LAL expertise on photo-injector
  - Currently: **Externalise** the machining of the pieces assembly will take place at LAL

(matching with STDM planning)

Operation frequency	2998,55 MHz
Charge	1 nC
Laser wavelength, pulse	266 nm, 100 µJ
RF Gun Q and Rs	14400, 49 Mâ„¦/m
RF Gun accelerating gradient	80 MV/m @ 5 MW
Normalized emittance (rms)	4.4 mm mrad
Energy spread	0 %
Bunch length (rms)	5 ps



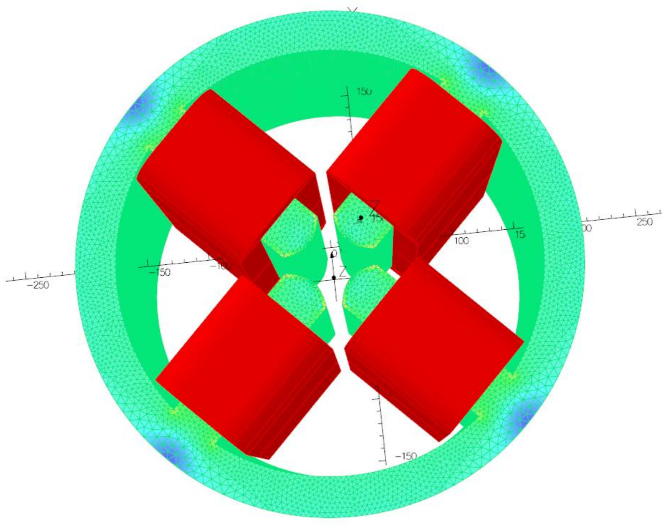


research instruments

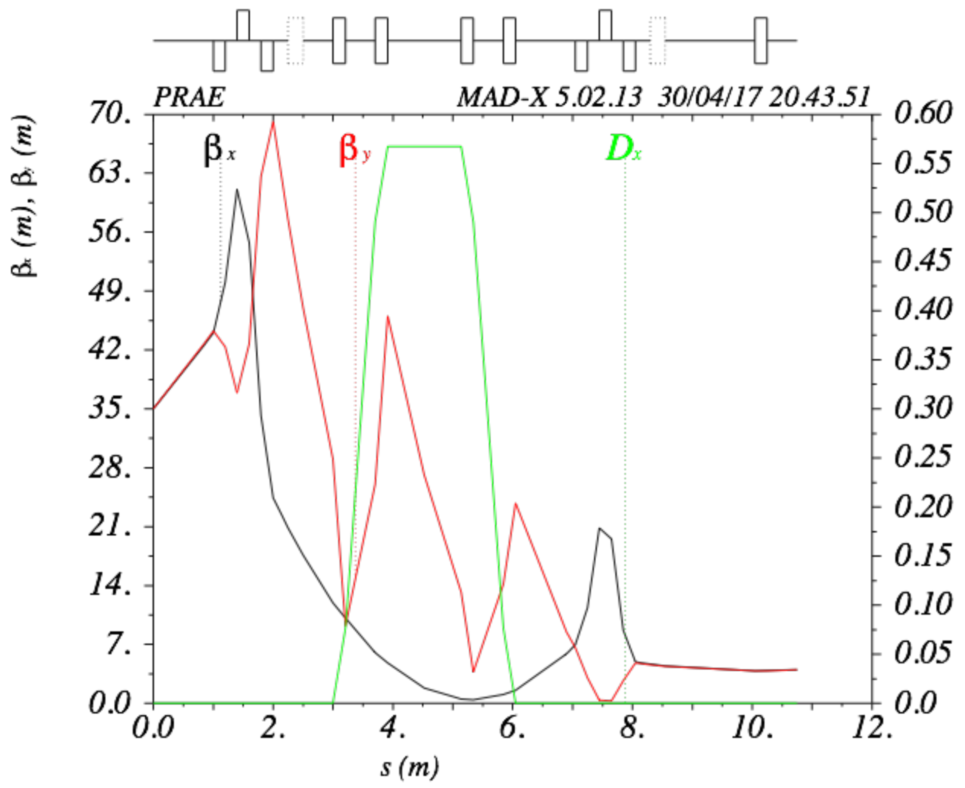
RF frequency	GHz	2856
Repetition frequency	Hz	50
Max RF input power	MW	40
Average accelerating gradient	MV/m	23.5
Total length	m	3.5
Type		TW

- **High-gradient linac:**
  - Initially: PRAE accelerator should profit from PMB-LAL accelerating section (HGAS)
  - Currently: Others options are being considered: RI Research Instruments GmbH, Euclide Techlab.
- **High-RF powering:**
  - Second generation SLAC modulator from S-band old 30 GeV linac being dismantled
  - The klystron characteristics has been identified and the technical call tender finished

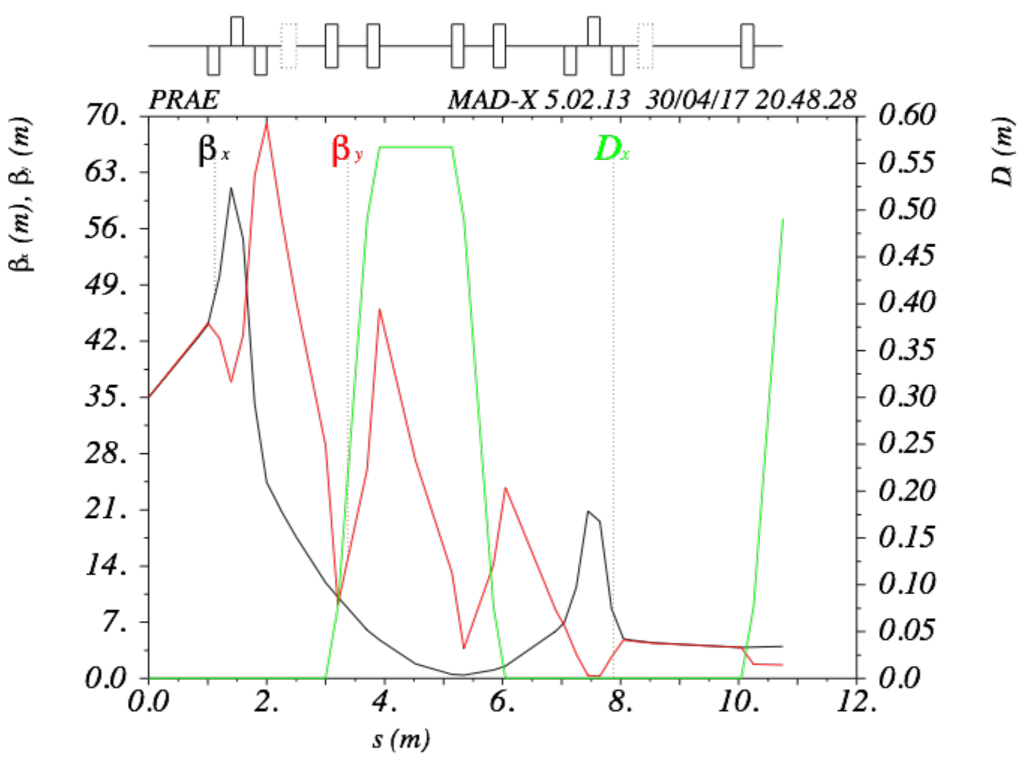
Magnet and optics calculations



- ➢ **Design of the accelerator magnets** (solenoids, dipoles and quadrupoles) **ongoing**
- ➢ **Preliminary beam dynamics simulation:** done with ASTRA and RF-track codes
- ➢ **Optics design and simulations**
  - Two triplets, flexible final conditions
  - with a Energy compression System (ECS) and a dedicated Beam Energy Measurement



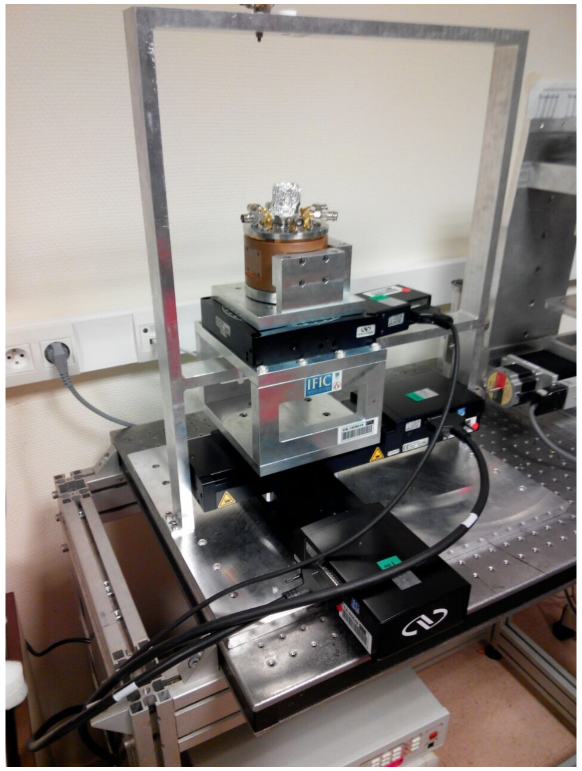
Direct line: ProRad and Radiobiology



Deviated line: Instrumentation

Progress summary

- **Beam dynamics simulations:**
  - **4 Master students internships**
  - **Post-doc 2018/2019 (P2IO/IN2P3)**: beam calculation and implementation

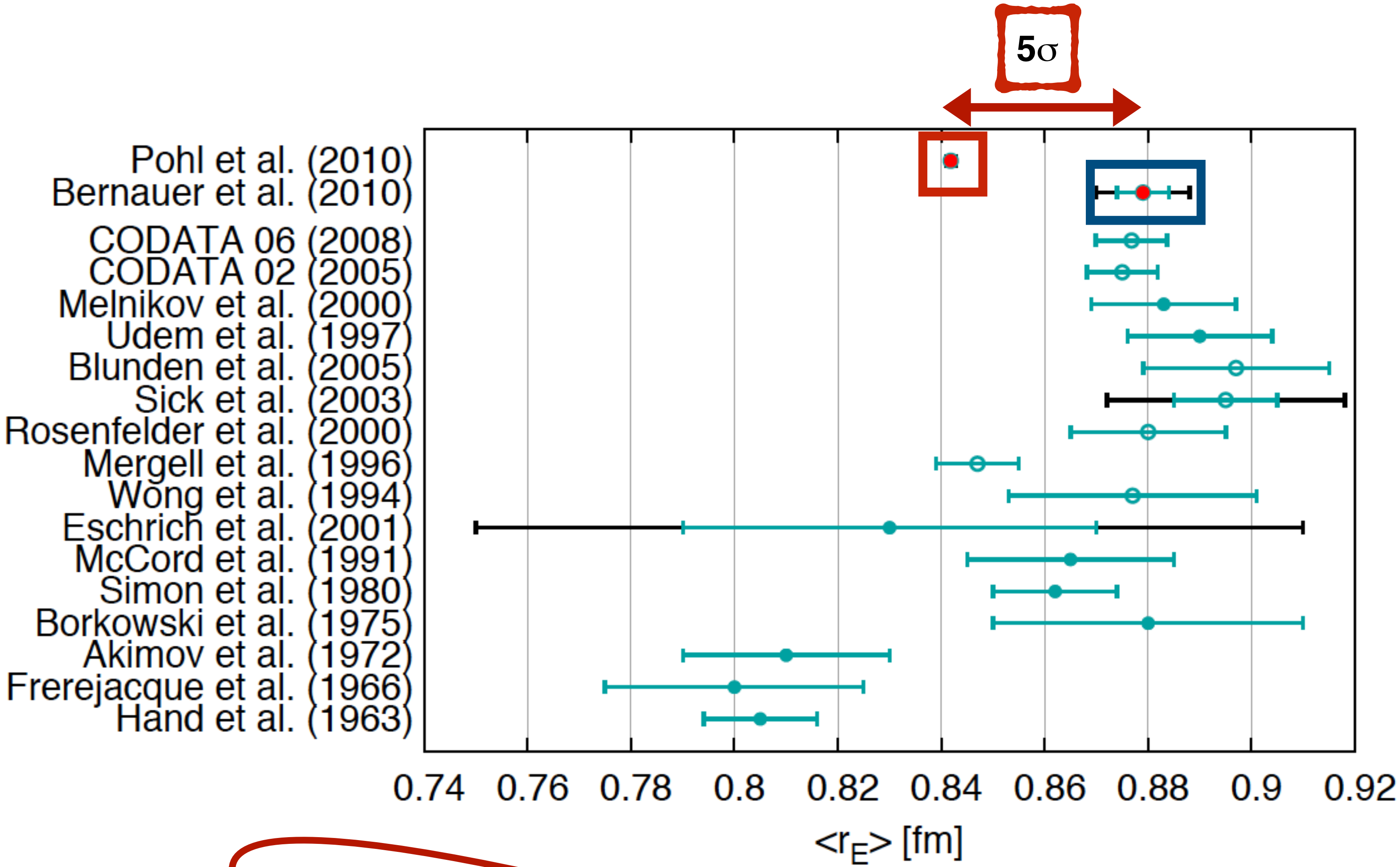


- **Started the Beam Positioning Monitor tests** *(test bench at IPNO):*
  - Master student internship

- **Construction progress**
  - Order RF gun, klystron and linac RF early 2018
  - Visit at SLAC (December) to recuperate accelerator parts

- **Communications PRAE and Accelerator:**
  - IPAC 2017: proceeding on preliminary beam optics calculation and global project JACoW (2017) THPVA079
  - VHEE Radiotherapy 2017 *(Cockroft Institute, Daresbury)*: invitation, PRAE Accelerator & Medical
  - French-Ukrainian workshop *(LAL),* KINR and KIPT *(Ukraine, March 2017)*
  - SFP 2017 : PRAE *(Roscoff)*
  - French-Bulgarian workshop *(Arbanasi), (Bulgaria, April 2017)*

Motivations: the Proton Radius puzzle



r_p = 0.84184±0.00067 fm

r_p = 0.87900±0.00800 fm

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

Muonic hydrogen spectroscopy

Direct measurement

(10 times more precise)

Electron scattering experiments

Indirect measurement

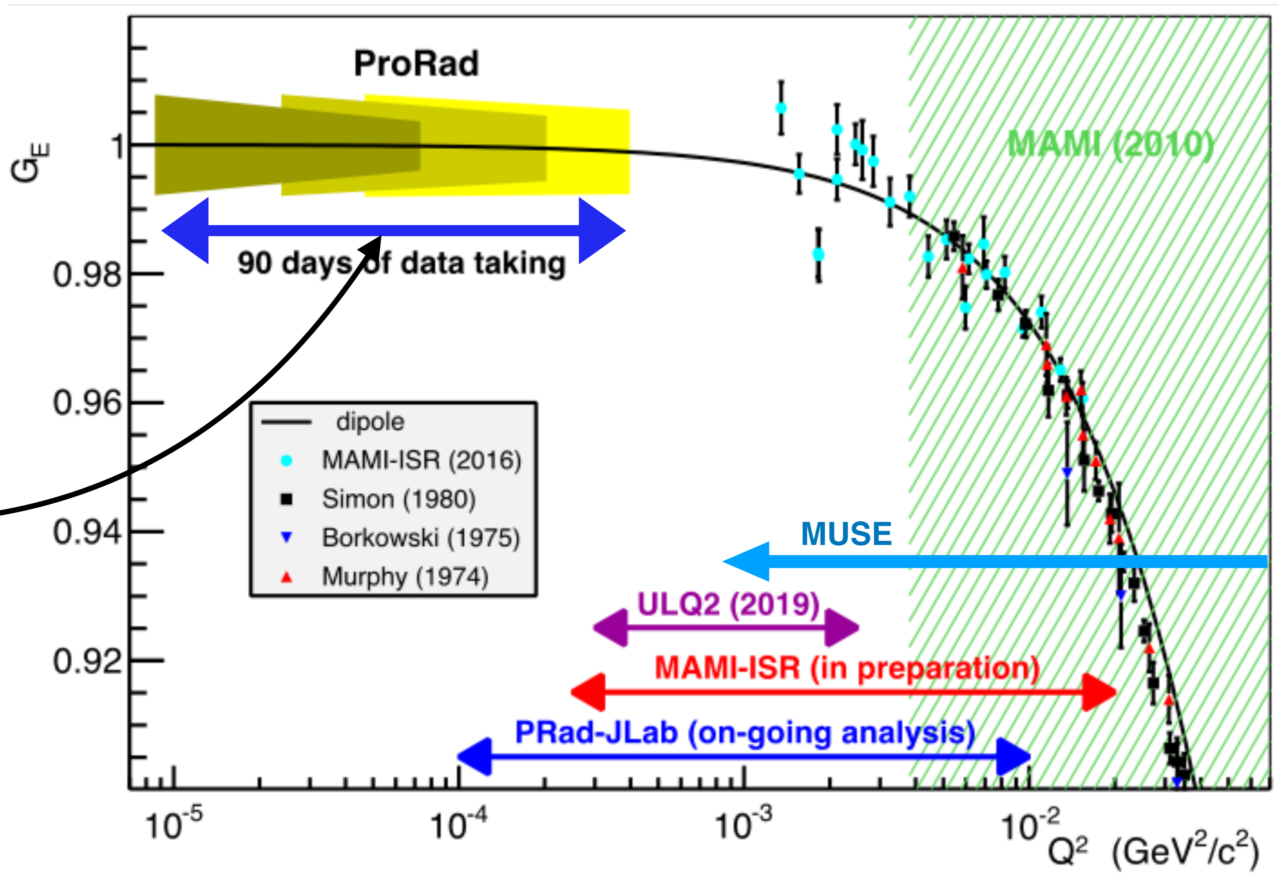
(extrapolation of Form Factor data to Q^2 =0)

The proton looked smaller to muons than it did to electrons

ProRad Goal

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

A linear region in the form factor:
'Extrapolation with no dependence on non-linearities'



Foreseen results:
- **A better knowledge of the dependence of Form Factor on Q^2**
- **A significant impact on the measurement of the proton charge radius**

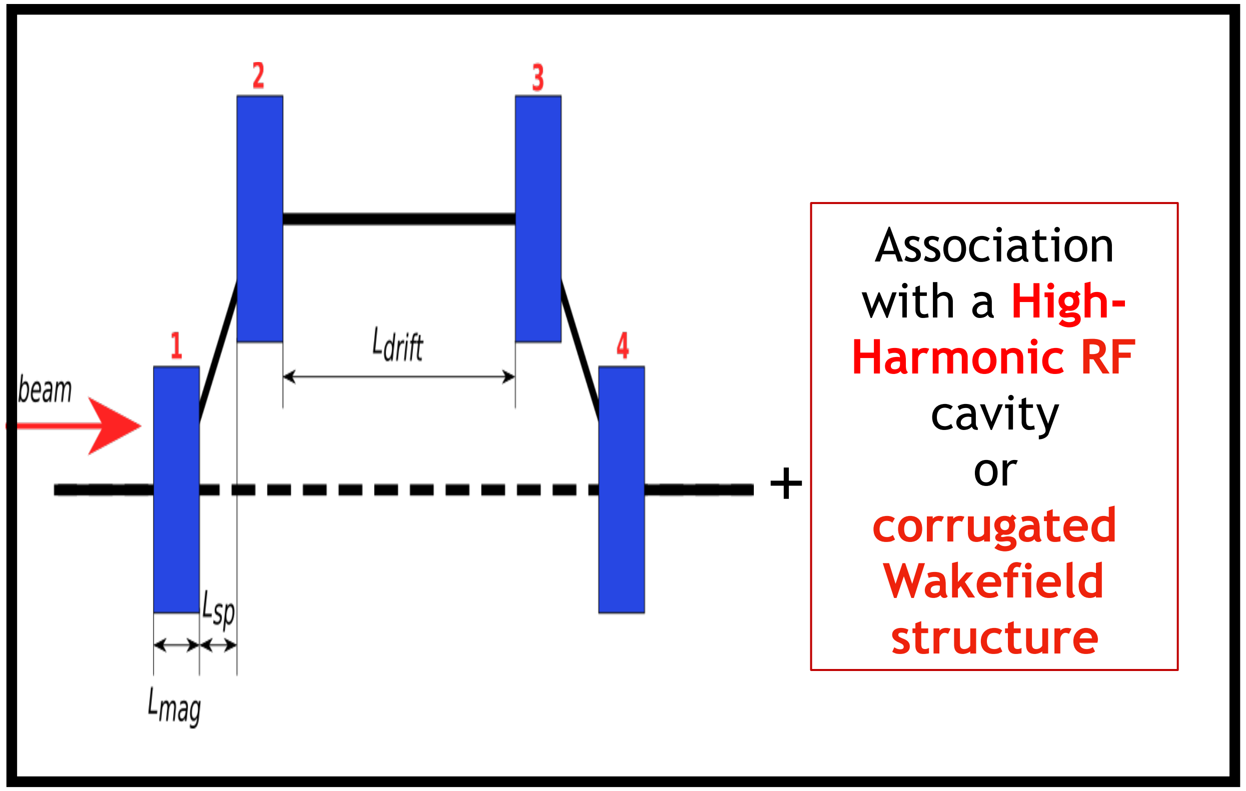
Progress summary

ProRad experiment requirements:

- High precision beam: **Reduced energy dispersion** **δP/P = 5x10⁻⁴**
- Precise knowledge of the beam energy **δE/E = 3x10⁻⁴**
- A stable target
- Optimised measurement of the scattered electron energy and position

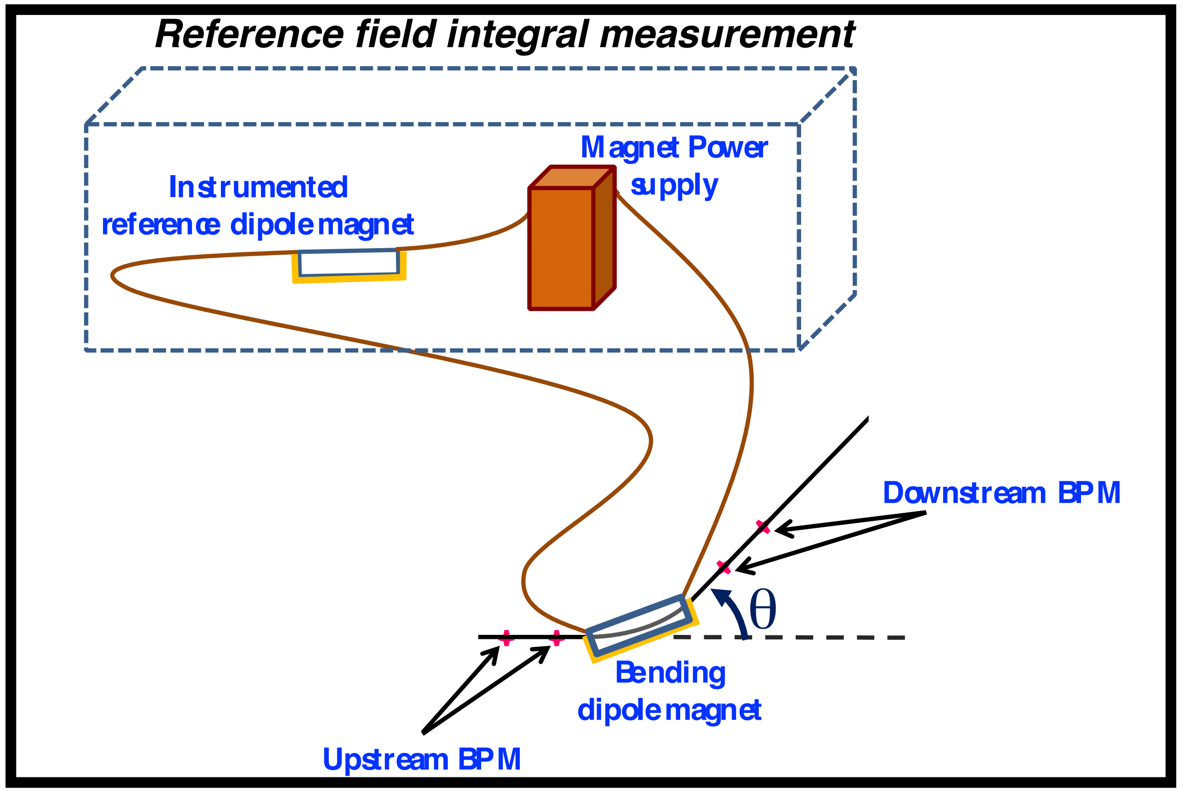
$$E = \frac{c}{\theta}\int B dl = \frac{c}{\theta} I_B$$

ECS



+

Beam energy measurement

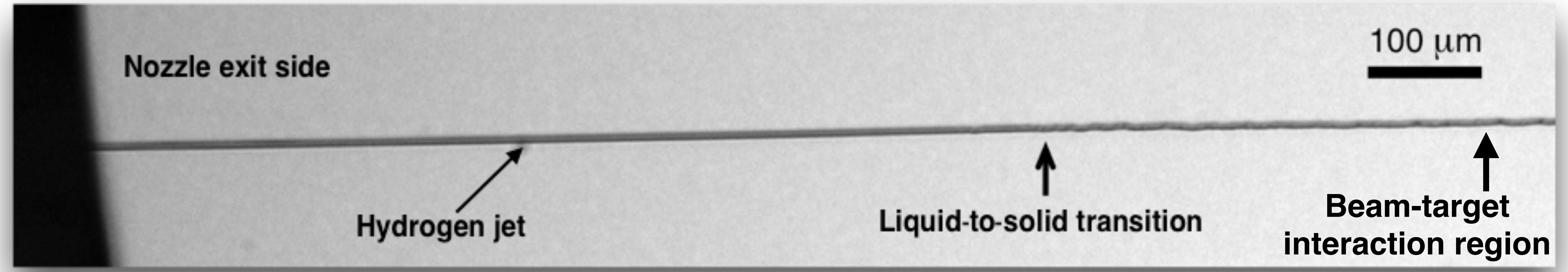


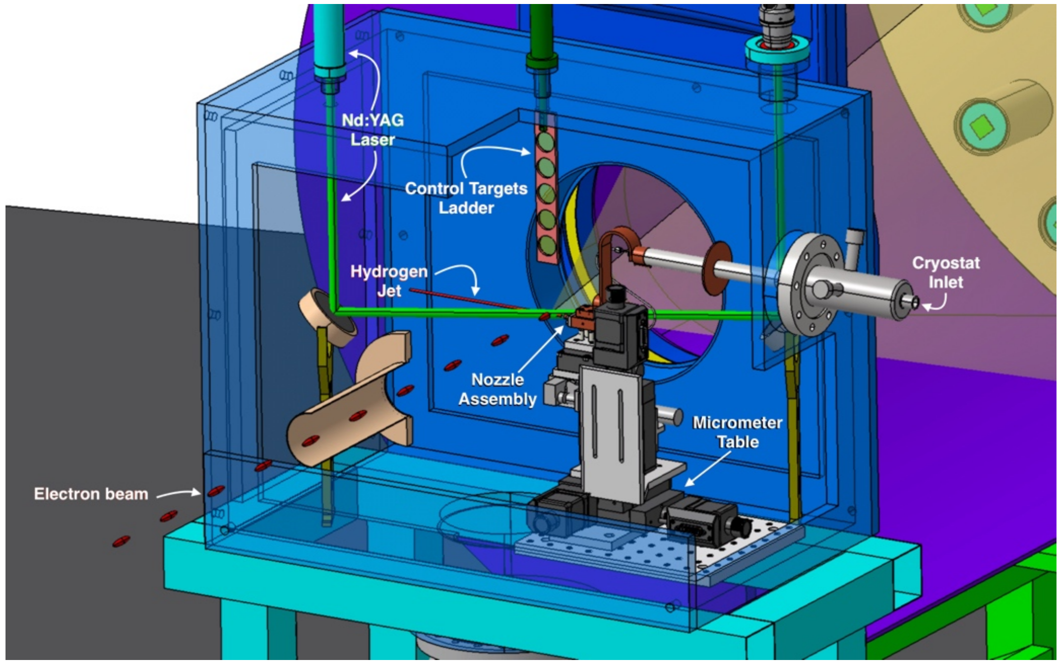
References: J.B. Flanz et al., "Energy Compression System Design for the MIT-Bates Accelerator Center" 1991 IEEE
T. Asaka et al., "Design of the ECS at the Spring8 Linac EPAC 2000"
Schedler et al., " A new high-current and single bunch injector at ELSA" LINAC 2014
"K.L.F. Bane and G. Stupakov. Corrugated pipe as a beam dechirper" NIM A 690 (2012)
Guetg, M.W. et al., "Commissioning of the RadiaBeam / SLAC Dechirper." United States: N. p., 2017. Web.
D. Marchand, Doctorate Thesis, Université Blaise Pascal, Clermont-Ferrand, 1998

Progress summary

ProRad experiment requirements:

- High precision beam: **Reduced energy dispersion** **δP/P** = **$5x10^{-4}$**
- Precise knowledge of the beam energy **δE/E** = **$3x10^{-4}$**
- A stable target
- Optimised measurement of the scattered electron energy and position





Requirements:
A very stable, windowless, and self-replenishing target of 15 *µ*m diameter

Ultra cold liquid technology developed at Frankfurt University

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Progress summary

ProRad experiment requirements:

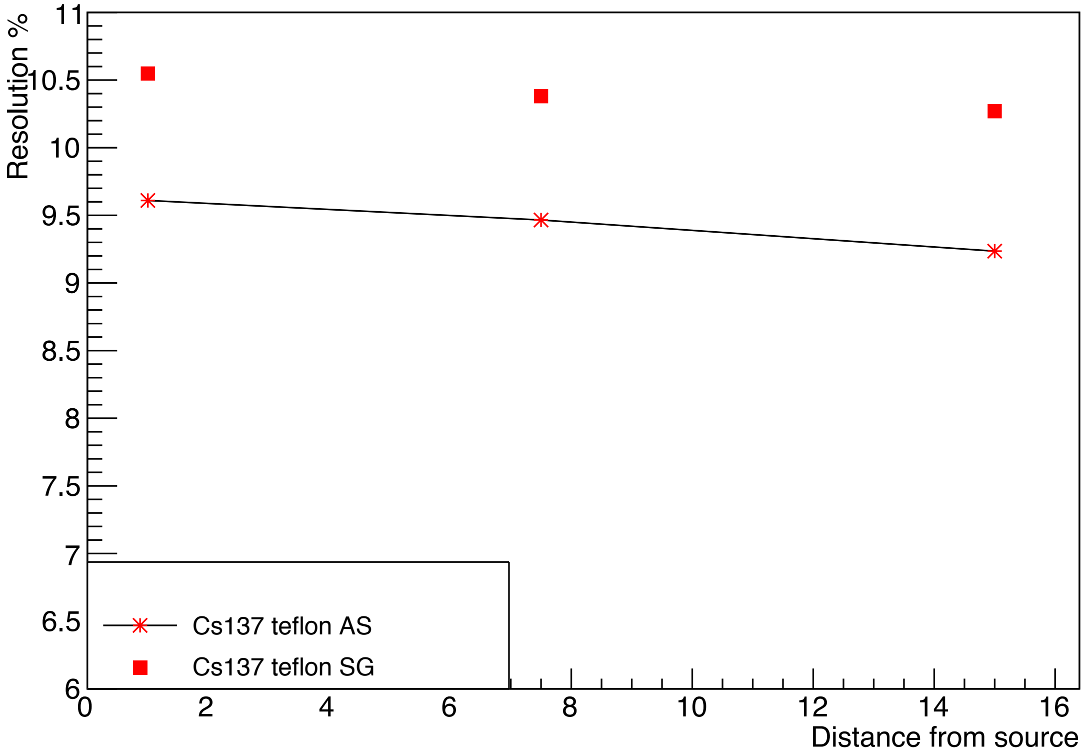
- High precision beam: **Reduced energy dispersion** **δP/P** = **$5x10^{-4}$**
- Precise knowledge of the beam energy **δE/E** = **$3x10^{-4}$**
- A stable target
- Optimised measurement of the scattered electron energy and position

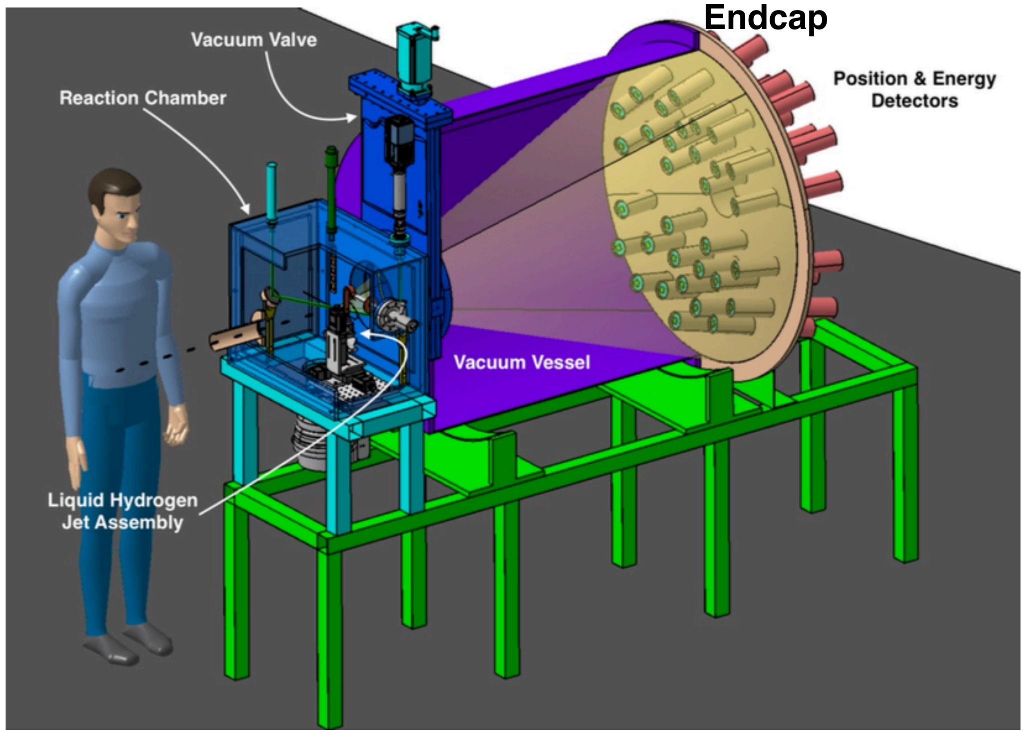
32 elementary detectors placed at 5 different scattering angles at a distance of 1.5 m from the target

Each elementary detector made of

- 2 planes of scintillating fibres (position)
- A cylindrical BGO crystal (energy)

Crystals tests started: additional tests programmed at ALTO (e^- beam) and CORTO (cosmics)





Progress summary

Experiment:

- ➢ **Detector conception** in a very elaborated stage *(full Geant4 simulation of the detector)*
- ➢ **Beam energy measurement technique** (first studies)
- ➢ **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 1L3/1M1/1M2 **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 collaboration: The GWU of Washington, the JGU of Frankfurt, and the LPC of Caen joined the ProRad team

Advantages of VHEE beams

VHEE beams: advantages vs MV photons

- ✓ ***Very good dosimetric properties*** **:** sharp lateral penumbra, flat longitudinal profile, relative insensitivity to tissue inhomogeneities
- ✓ ***Magnetic collimation***: pencil beam scanning, precise intensity modulated irradiations *(DesRosiers et al., Indiana)*

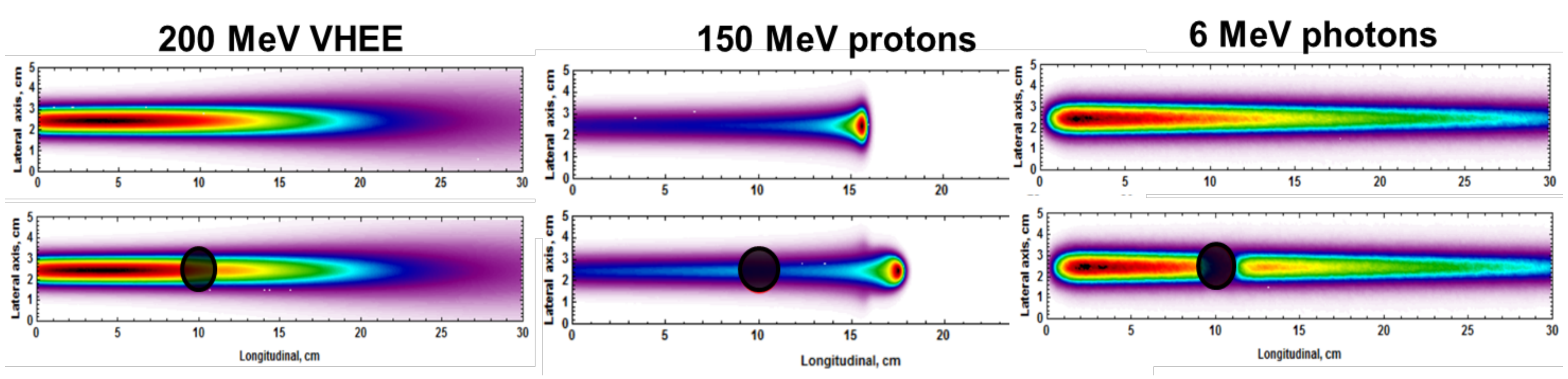
Clinical cases comparison :

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

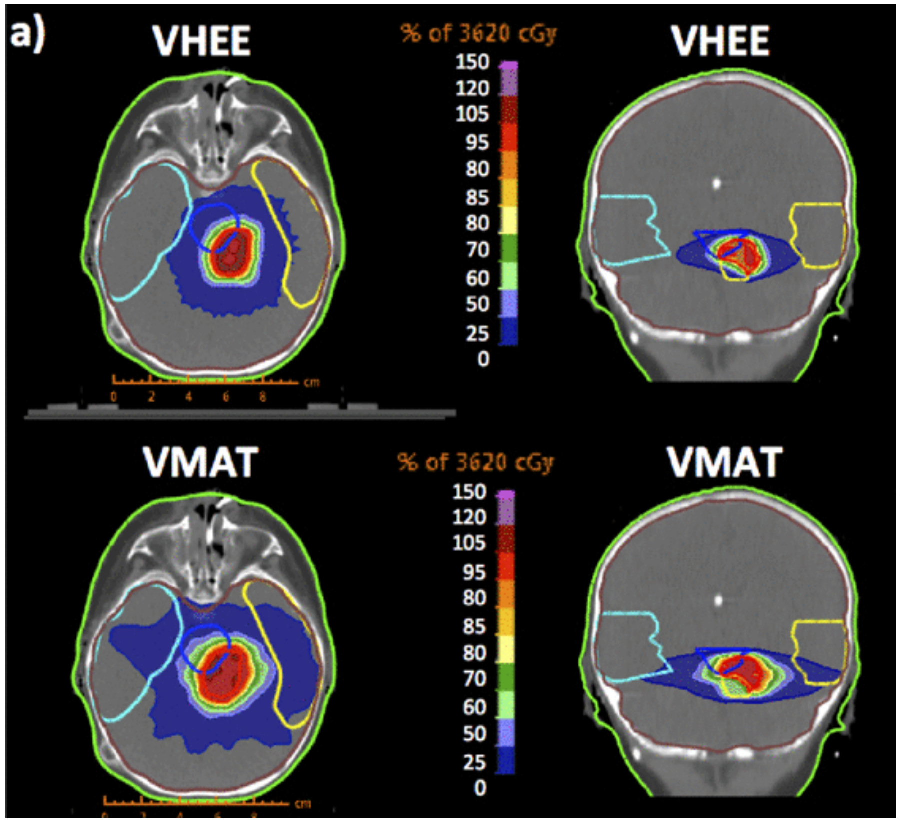
VHEE beams: advantages vs protons

- ✓ ***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)

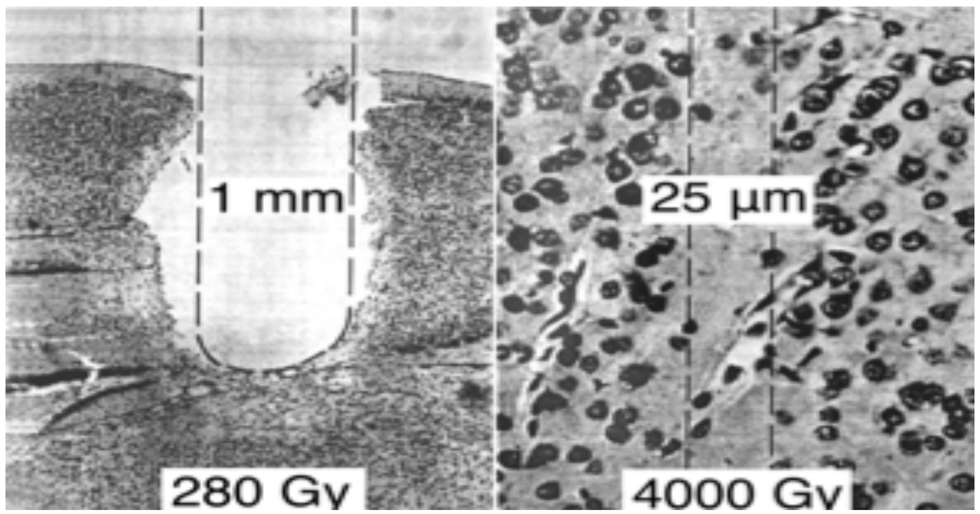


Brain tumour dose maps for 100 MeV VHEE and 6 MeV volumetric modulated arc photon therapy (VMAT) Bazalova-Carter, 2015

Spatial fractioning of dose

Spatial fractionation of dose and mini-beam radiation therapy (MBRT):

Very small field size (< 1 mm^2)

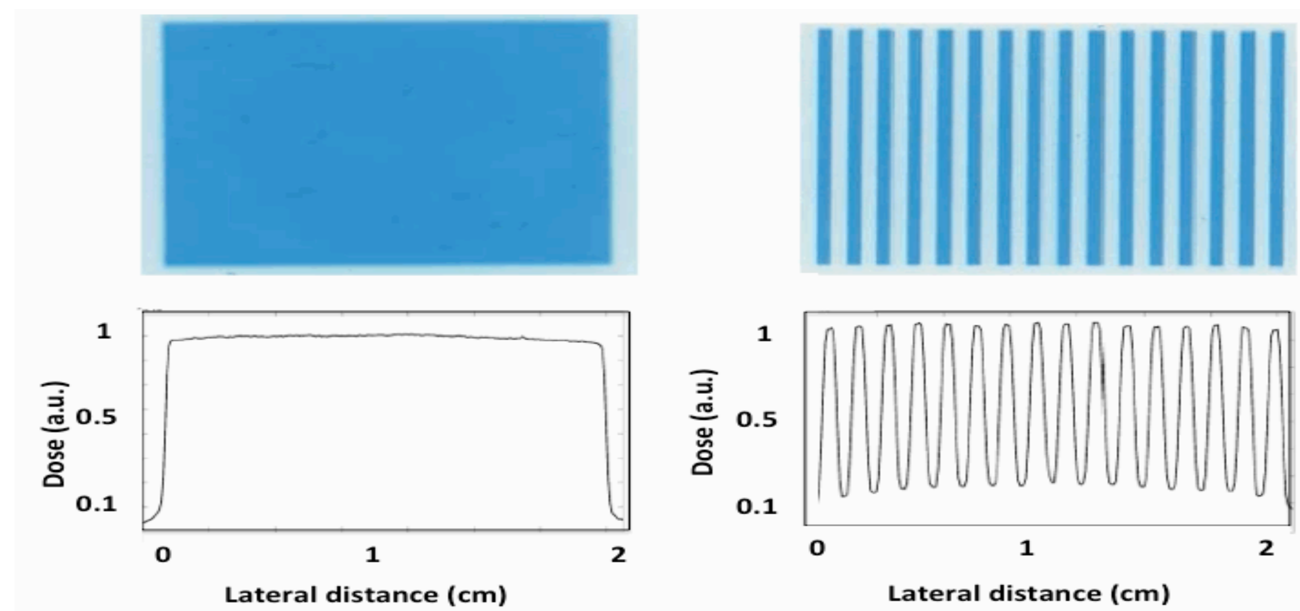


Zeman et al., Science (1959)

Spatial fractionation of dose

Conventional RT

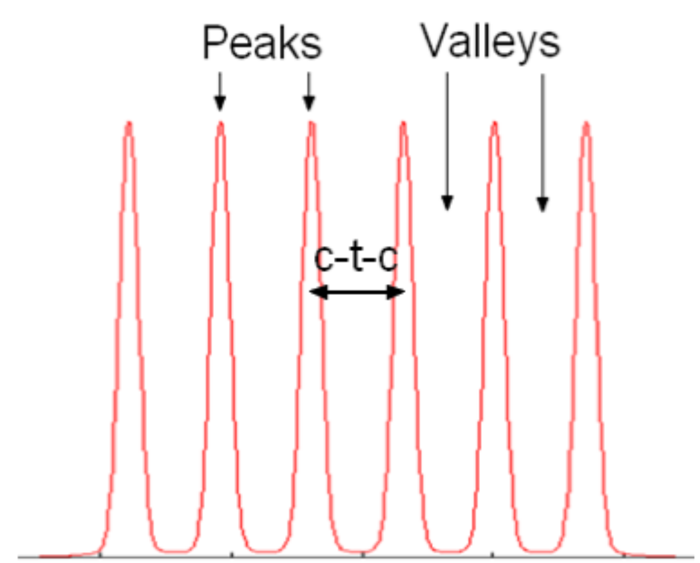
Fractionated RT



→ **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 22 Gy

Grid therapy with magnetically collimated VHEE beams

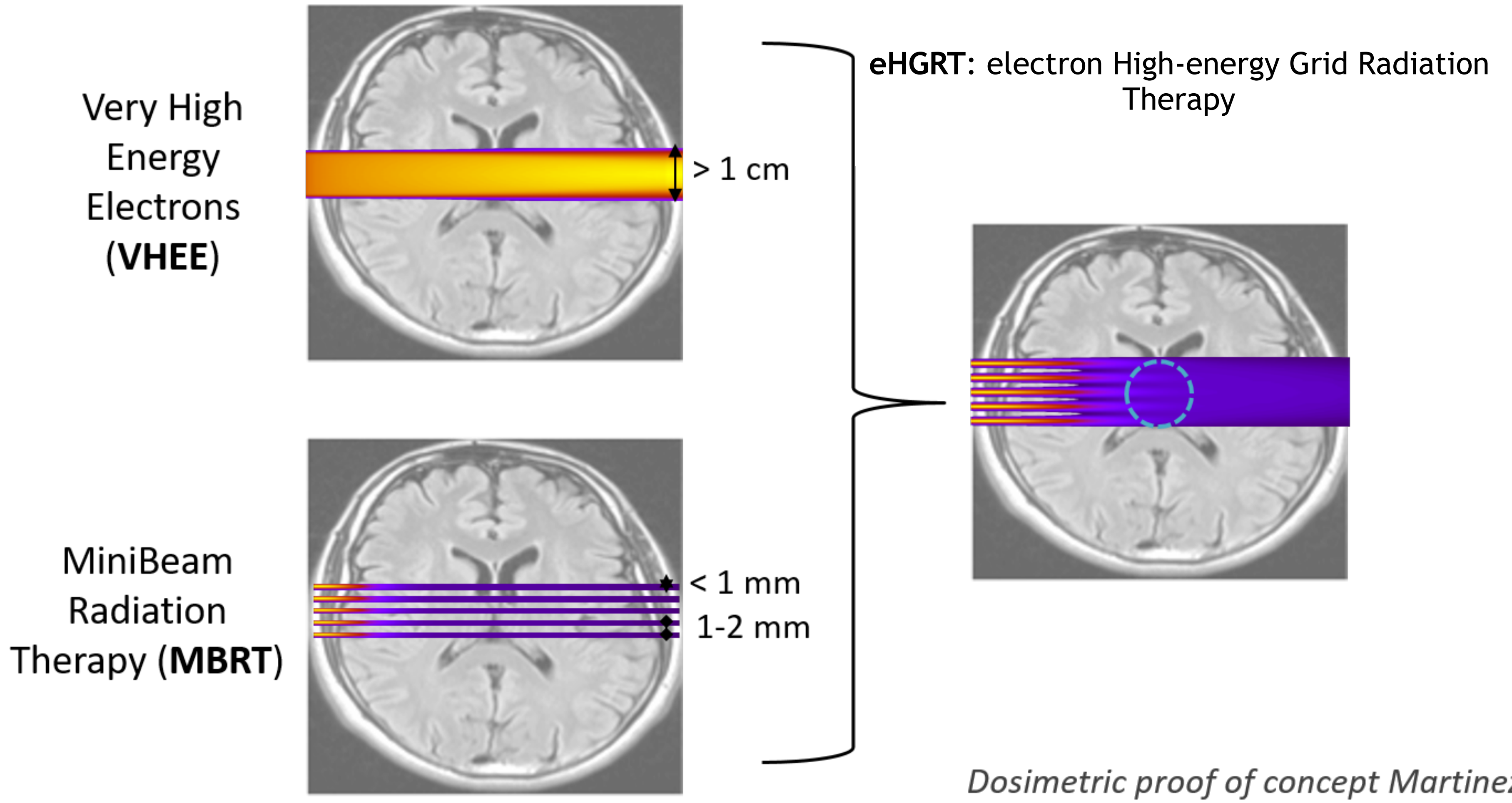


$$PVDR = \frac{D_{\text{peak}}}{D_{\text{valley}}}$$

↗ PVDR = ↗ tolerance of healthy tissues

eHRGT

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

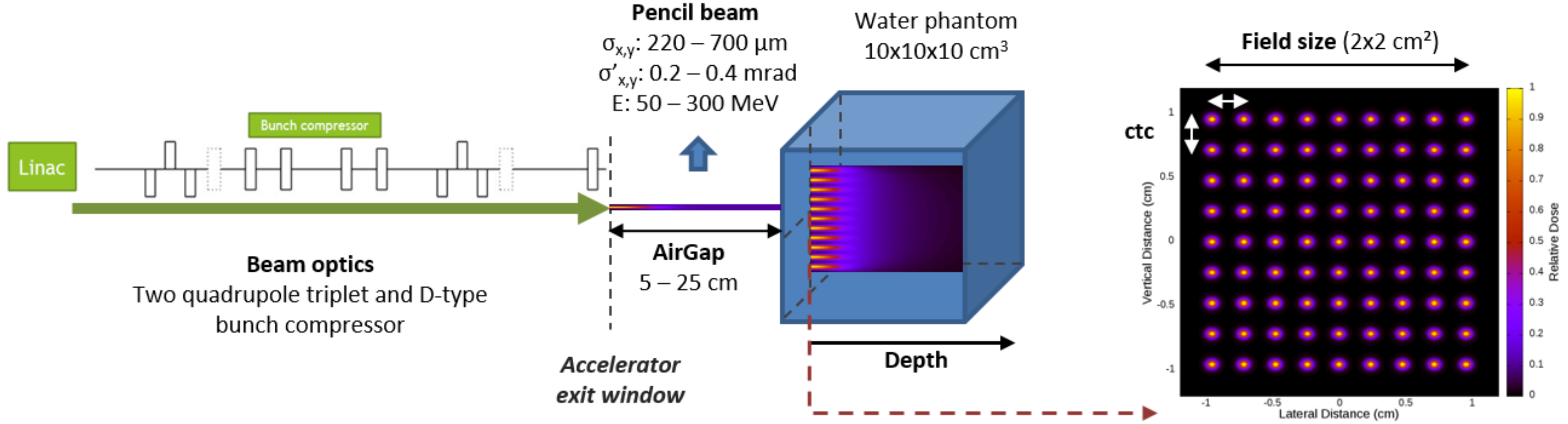


Dosimetric proof of concept Martinez et al., Med. Phys. 2015

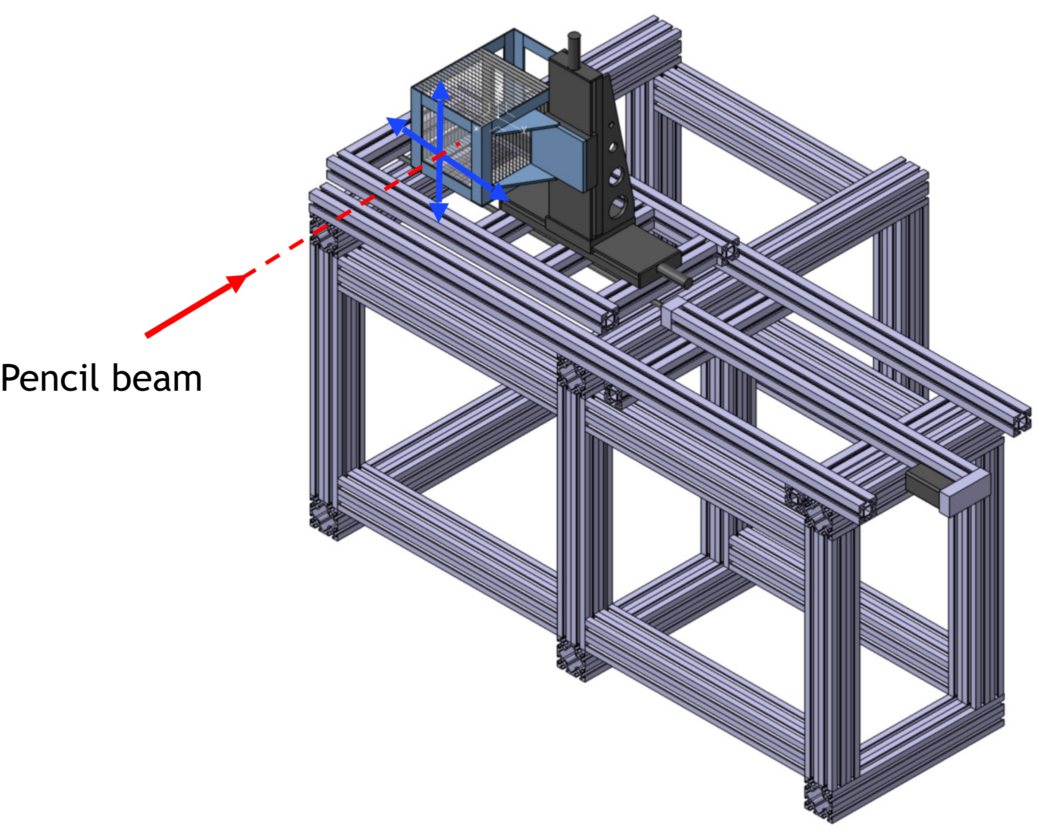
→ **At PRAE:** objective to perform all the numerical and experimental dosimetric validation until the *in vivo* proof of concept

Preliminary results

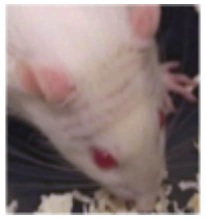
Beam-optics calculations for preclinical experiments :

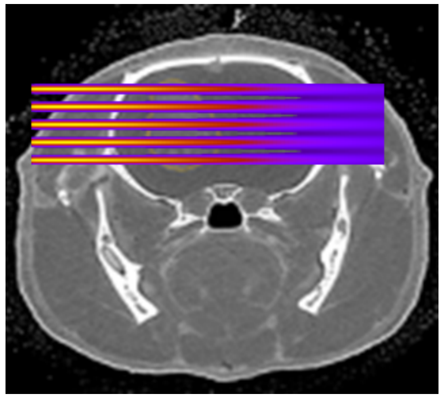


Transverse pattern of a VHEE grid-therapy irradiation at phantom entrance

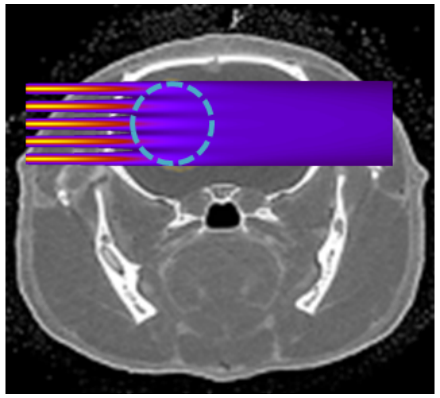


Work in progress in rat-head CT images:





140 MeV, σ 250 µm
Optimization of tissue sparing



70 MeV, σ 350 µm
Tumor control optimization

Progress summary

- **Monte Carlo studies**:
  - Beam optics optimisation: 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 additional budget —> support from expertise and animal facility of Institut Curie…

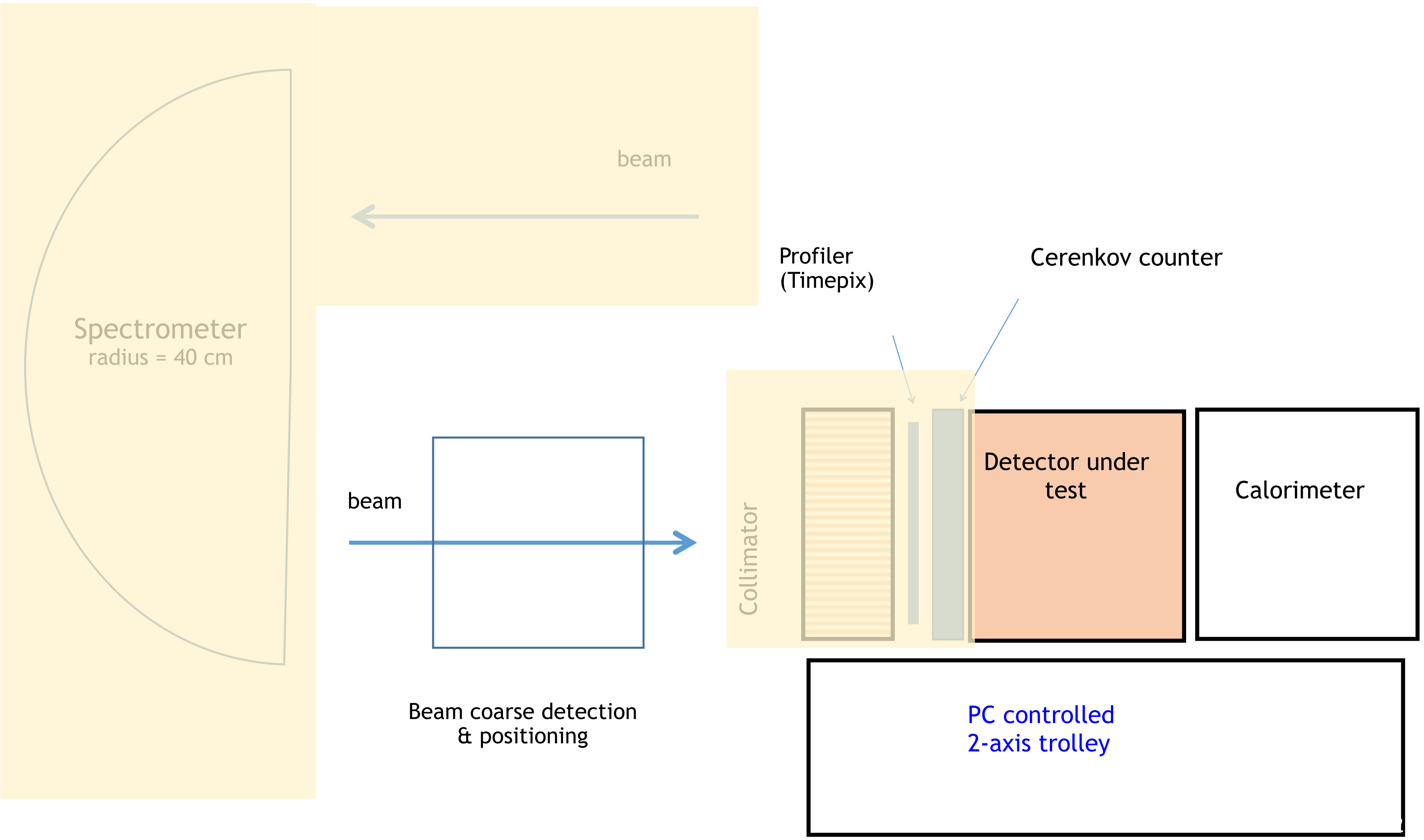
- **Interest of the PRAE beam** for other radiobiological experiments: « Flash-effect »

institutCurie

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 digitisation channels with the WaveCatcher digitisation system on a NARVAL-based data acquisition
        - motorised table for scanning (<500-μm accuracy)
    - No need to place the detectors in vacuum

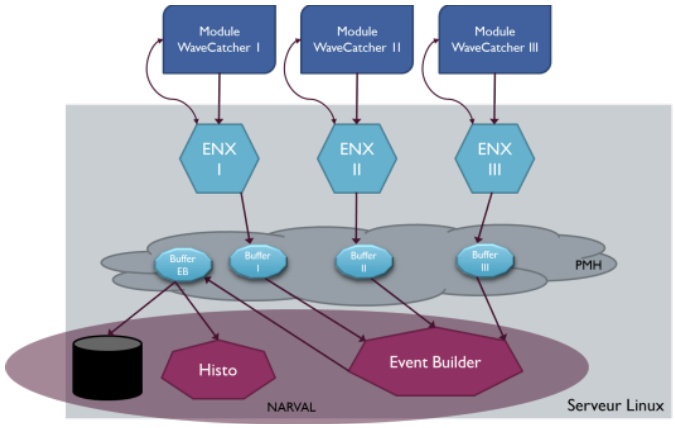
Phase I



User-Friendly interface/ programs for control and analysis

DAQ + slow control

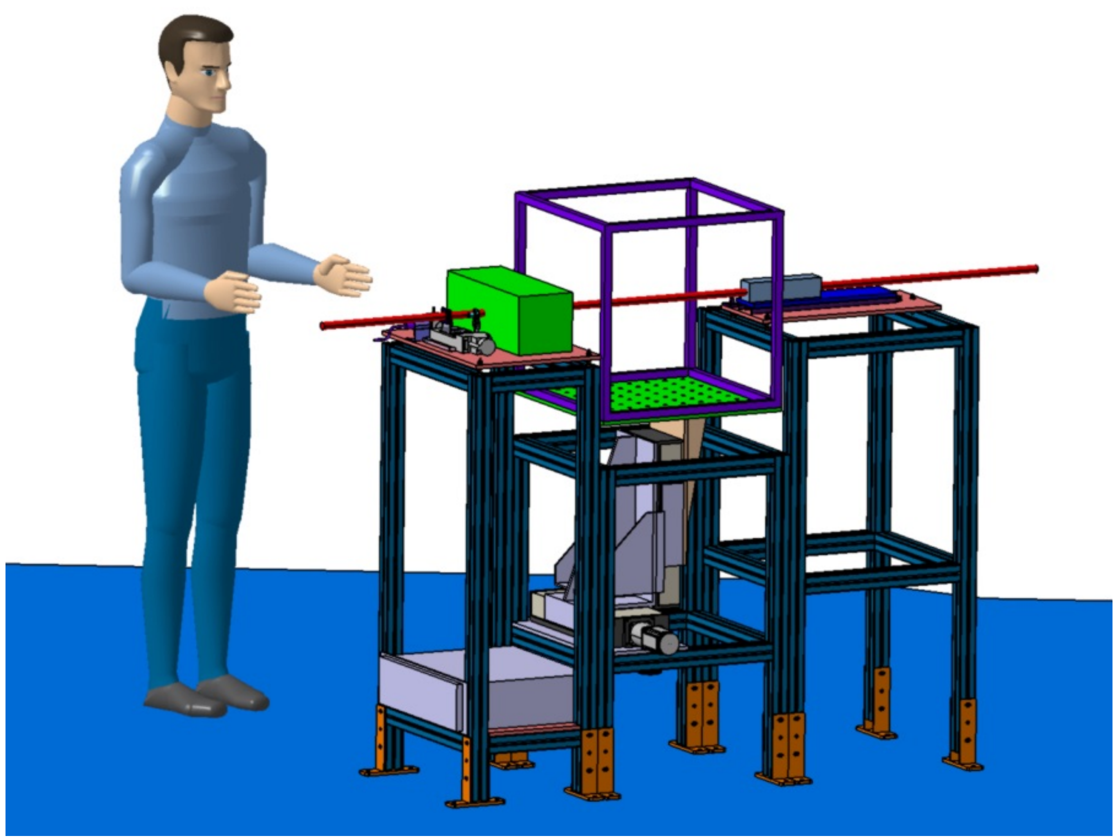
- 32 digitization signals (WaveCatcher) for the user
- DCOD = NARVAL + ENX
- Possible online signal processing

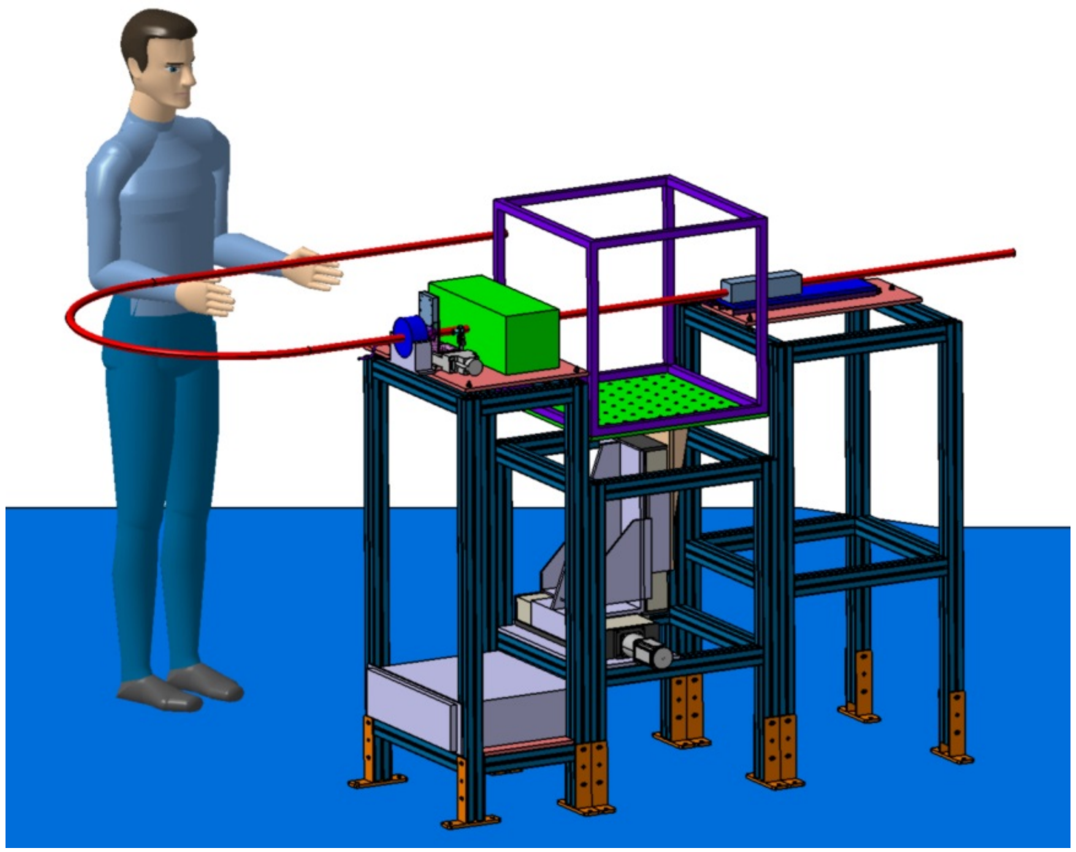


→ Benefit for ProRad detector tests

Progress summary

- ➢Shifts due to the funding situation
- ➢« Phase 1 » : no spectrometer (75 k€) —> no TimePix (10 k€)
- ➢Mutualise purchases
  - ○Scan motor with radiotherapy requirements
  - ○Share ProRad equipment (supplies, PMT, DAQ)





Budget and planning

- **Fundings**:

Equipment

P2IO		514 k€
SESAME		1070 k€
LAL/IPNO		100 k€

+ Infrastructure → CPER

2 post-docs (P2IO/in2p3)

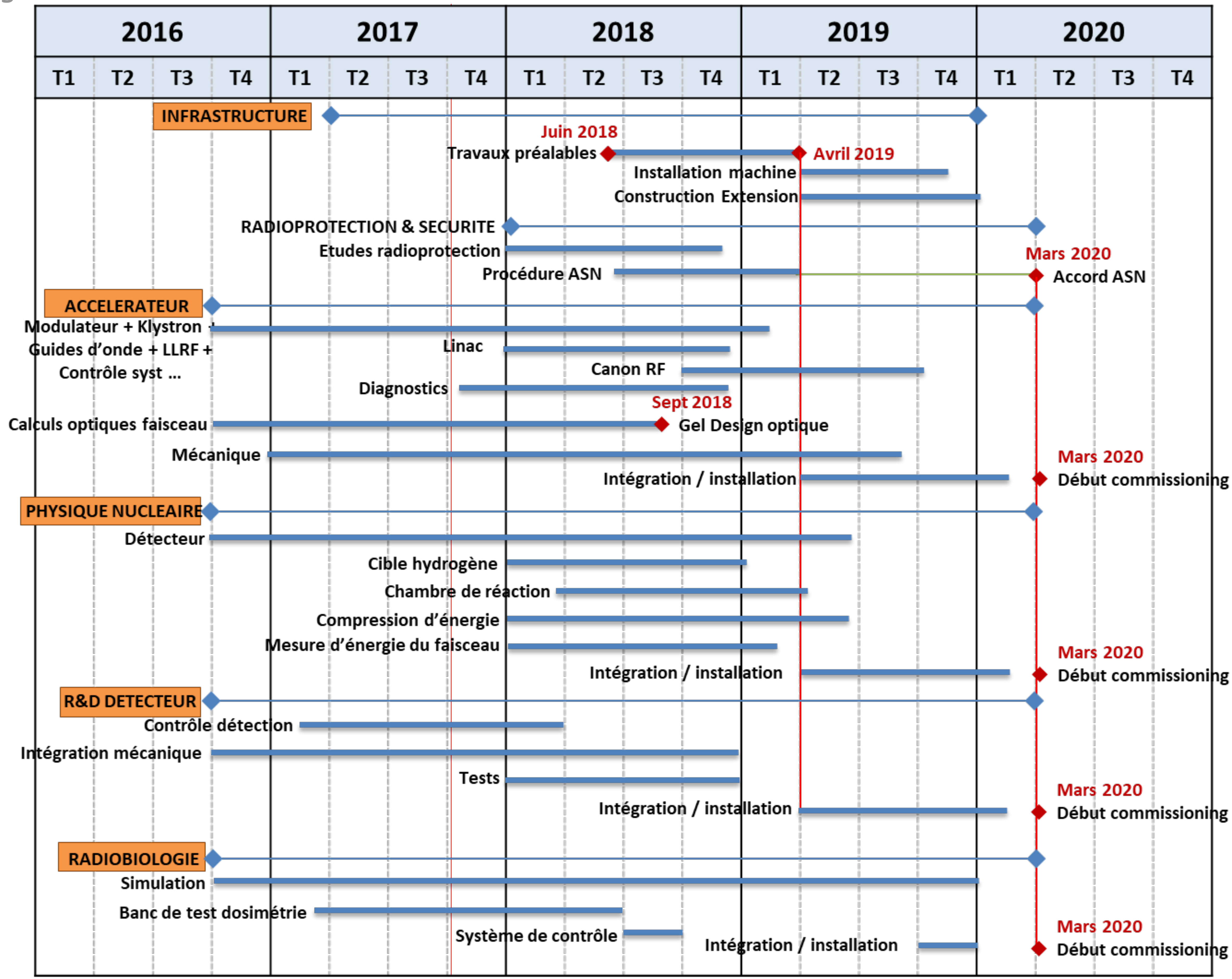
TOTAL : 1684 k€

- **PRAE cost: Phase 1**

  →Machine with recovered and shared equipments = 2160 k€
  (Laser PHIL, SLAC elements as modulators, BPM, wave guide…)

  → **476 k€ missing**, search for other funding sources and new collaborators

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



2016
2017
2018
2019
2020
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
Mars 2020
Intégration / installation
Début commissioning
PHYSIQUE NUCLEAIRE
Détecteur
Cible hydrogène
Chambre de réaction
Compression d'énergie
Mesure d'énergie du faisceau
Mars 2020
Intégration / installation
Début commissioning
R&D DETECTEUR
Contrôle détection
Intégration mécanique
Tests
Mars 2020
Intégration / installation
Début commissioning
RADIOBIOLOGIE
Simulation
Banc de test dosimétrie
Mars 2020
Système de contrôle
Intégration / installation
Début commissioning

Summary

- **Advances in the four axes:** budget optimisation, equipment sharing
  - Simulation work: beam requirements for experiments, magnets, detector & table design, calorimeter testing…
  - Accelerator: a postdoctorate will start in 2018
  - ProRad: a postdoctorate started in 2017
  - Infrastructure: proposal for an extension of the building
- **Training, communication, collaboration:**
  - 7 intern students (L/M) *(2-4months)*, 2 postdocs
  - Presented in 10 conferences/workshop *(2 reference proceedings)*
  - Extended collaborations: LPC Caen, JGU Frankfurt, GWU Washington *(ProRad)*, Institut Curie *(Radiobiology)*
- **Project monitoring:**
  - 6 meetings/y with WP responsible, 3 meetings/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.

Main questions of P2IO scientific council last year:

Motivation for various applications: introduced throughout the slides

Education and training: the project already hosting intern students. The platform can serve for teaching purposes

Upgrade of existing building: covered by regional project via university

Safety/security requirements: new infrastructure defined, awaiting feedback from experts from institute curie

Involvement of oncologists: project aims at the phase of radiobiology **not yet, too early**

Operation and maintenance expenses:

- 1st phase ProRad and Radiobiology: funding from labs, P2IO and IDF
- 2nd phase Platform: contribution of labs technical services for operation with an objective of industrial attraction to achieve autonomy

Cost and timing: slides 28 and 29

Backup slides

Education and training:
- students TP for NPAC, GI: PRAE accel, detector, prorad experiments can serve as teaching platform
- by now hosted already >6 student internships, each for 2-4 months;
- 2 post-docs already started. Proposed 2 PhD theses (funding needed…).

Motivation for various applications:
- proton charge radius puzzle - low q2, new technique/approach, less model dependence in conclusions, ...
- radiobiology & radiotherapy : advantage over photon (dosimetry) and proton beams (cost), new approaches (grid, flash…)
- R&D detectors - lack of electron beam lines in the PRAE energy range ;
- potential of many more applications when adding accelerating sections *(radiotherapy as high-energy allow to decrease the lateral penumbra, material science…)*

Are oncologists already involved in the medical application of the project ?
- the project aims at the phase of radiobiology, so it is early to directly involve oncologists;
- CPO (Centre de Protonthérapie d'Orsay) already in the discussion and involved in other similar projects with imnc *(pMBRT)*

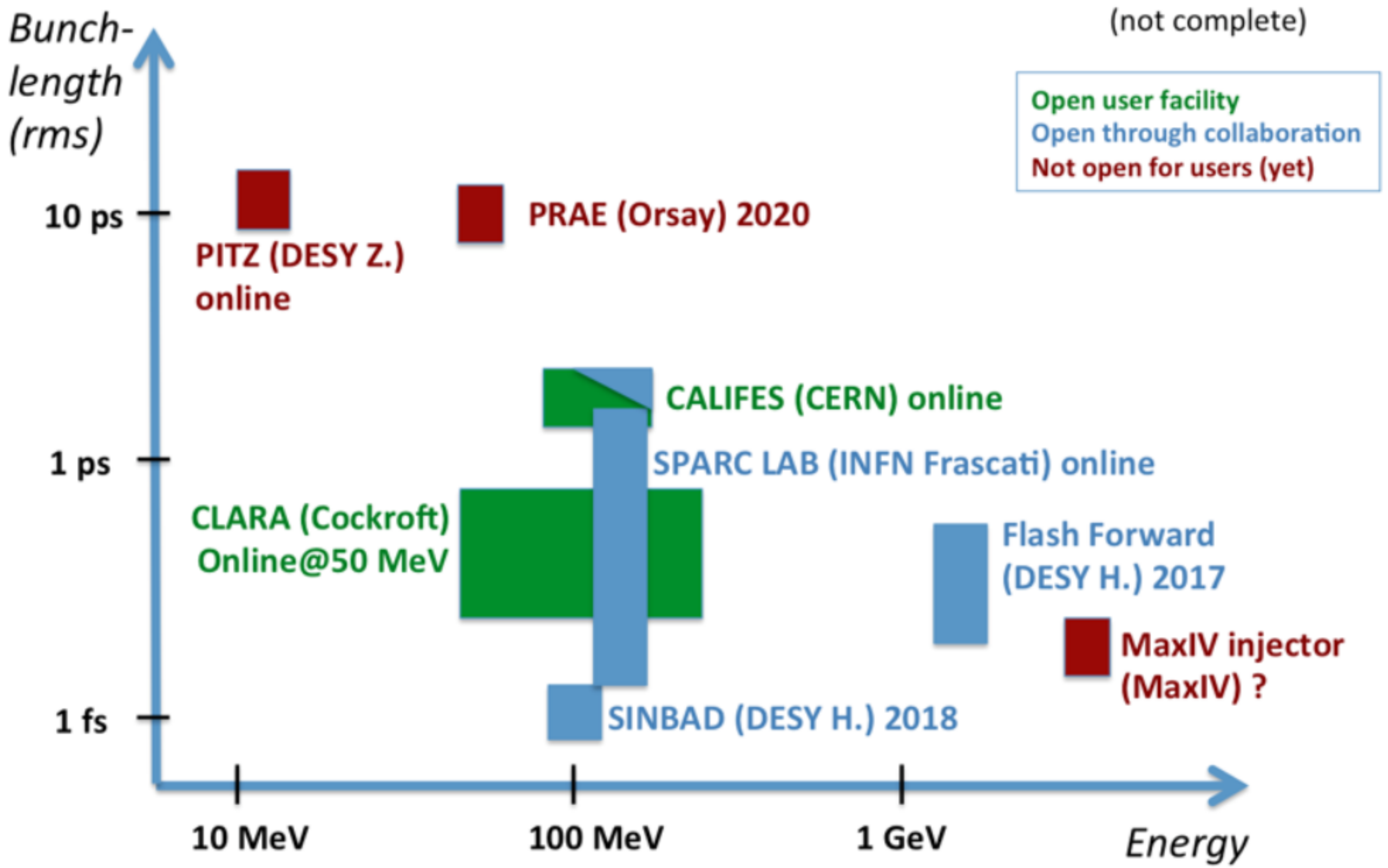
Compatibility of existing accelerator building with radiobiology and safety/security requirements:
- new building / infrastructure defined (Patricia/Mark), transmitted to the university; expert advices from Curie Institute;

Cost and timing:
- declared cost covered by P2IO, IdF region, contributions by laboratories.
- ProRad target financing is searched via France-Germany ANR, other partners.

Upgrade of existing building:
- fully covered by regional project via university; project launched and is with the university experts.

Operation and maintenance expenses over the lifetime of the project:
- Becoming plateform after the physics experiments already included in the prae project.
- 1st-phase Platform: contrib of technical services for operation + cost (lab)→ objective: industrial attraction, autonomy..

Present and planned European electron test beams



E. Adli - More details can be found at https://goo.gl/sn4dqP

Project Coordinator
Sergey BARSUK

Technical Coordinator
Patricia DUCHESNE

Scientific Coordinators

PA1 :	**Subatomic Physics**	Eric VOUTIER
PA2 :	**Radiobiology**	Yolanda PREZADO
PA3 :	**Detectors R&D**	Bernard GENOLINI
PA4 :	**Accelerators and Beam Instrumentation R&D**	Angeles FAUS-GOLFE

ACCELERATORS
Angeles FAUS-GOLFE

RF GUN
Mohamed EL KHALDI
RF LINAC
Mohamed EL KHALDI
LLRF
Mohamed EL KHALDI
HPRF
Maher OMEICH

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BEAM INSTRUMENTATION
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Sébastien BLIVET

INTEGRATION
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Denis DOUILLET

BEAM PIPES
Alexandre GONIN
Denis DOUILLET

BEAM DUMPS
Alexandre GONIN
Denis DOUILLET

VACUUM
Bruno MERCIER

INFRASTRUCTURE
Marc LANGLET

IMPLEMENTATION
Alexandre GONNIN
Patricia DUCHESNE

DEFINITION OF NEEDS
Marc LANGLET
Patricia DUCHESNE

MASTER WORK
Marc LANGLET
Patricia BERTHO
Patricia DUCHESNE

RADIOPROTECTION & SAFETY

RADIOPROTECTION & SAFETY
Patricia BERTHO
Sébastien WURTH

ASN PROCEDURE
Patricia BERTHO
Sébastien WURTH
Jean François LE DU

EXPERIMENTS
-

PA2
IRRADIATION CHAMBER
Sébastien BLIVET

SCANNING DIPOLE
Cynthia VALLERAND
Samuel MEYRONEINC

PA1
SUPPORT STRUCTURE
Kevin PRESSARD

REACTION CHAMBER
Christine LE GAILLARD

ENERGY MEASUREMENT
Dominique MARCHAND

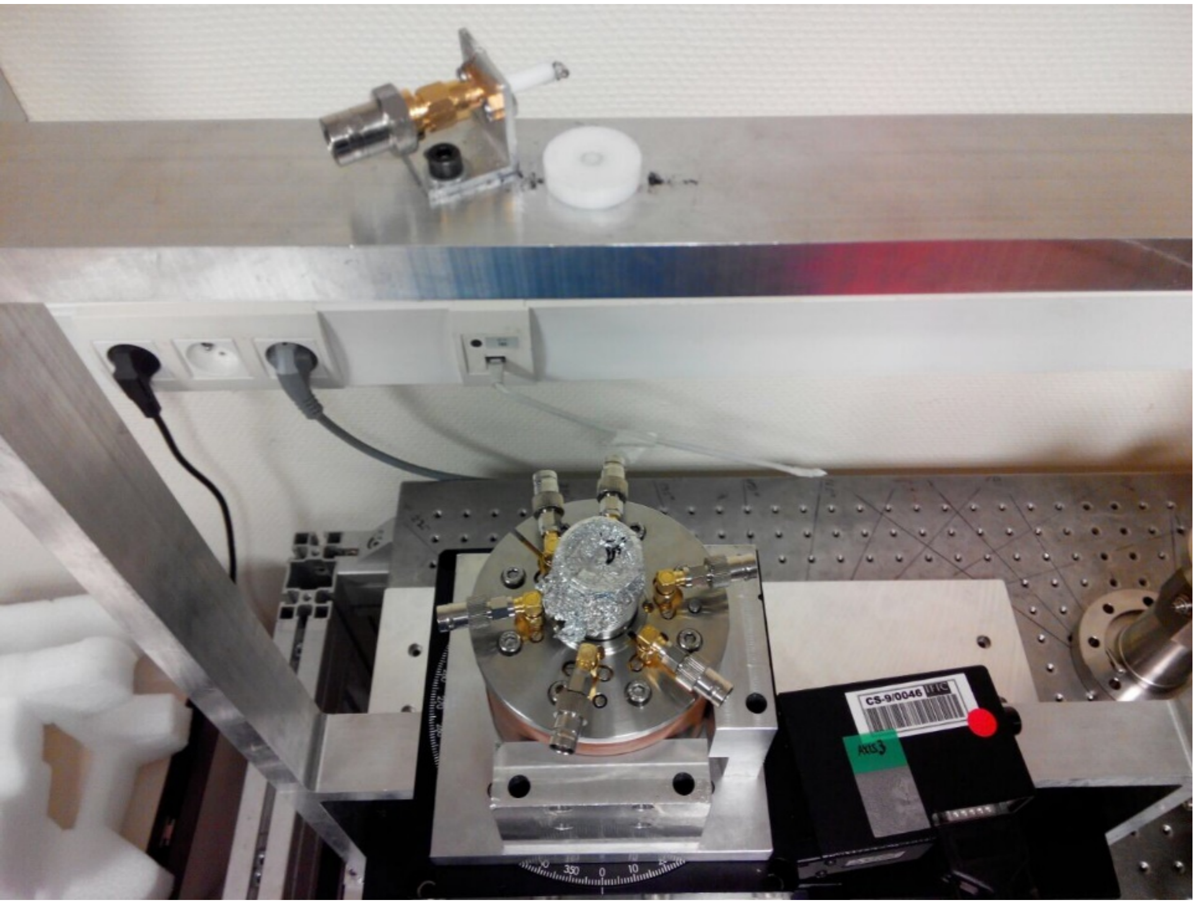
PA3
SPECTROMETRE
Sergey BARSUK

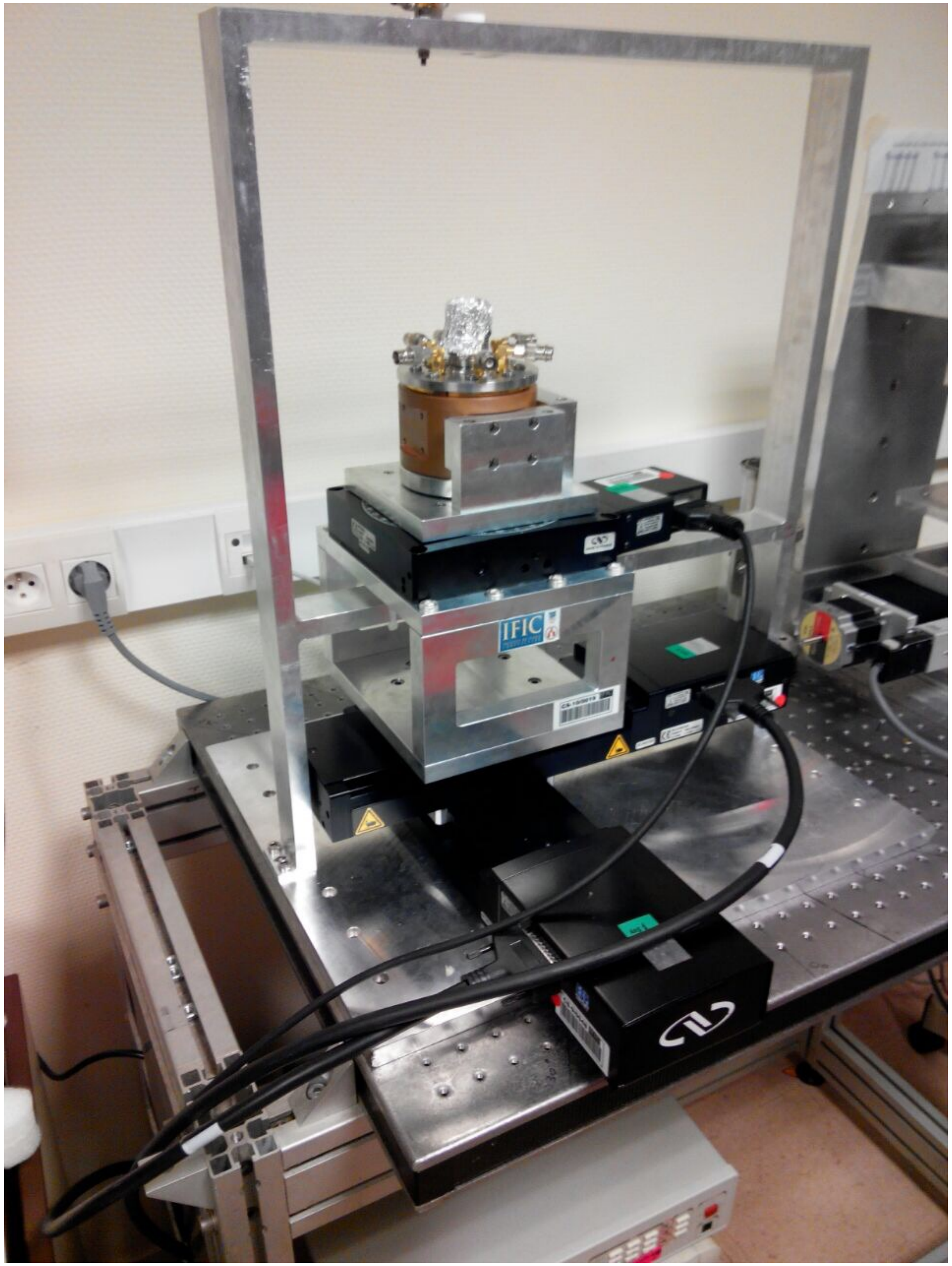
Giulia HULL

P. Ausset, M. Abdillah, C. Joly.
F. Fourier, A. Makarchuk

BPM TEST BENCH AT IPNO LABS.

On going work…





	Financement	Coût	2017	2018	2019	2020	Commentaires
		P2IO	SESAME	LABOS	?		
	Financement	Coût	2017	2018	2019	2020	Commentaires
PA2: Radiotherapy		75	0	21	54	0	
Sample Preparation	Pas de financ.	27			27		Particip. IMNC
Beam Irradiation Chamber	P2IO - 8177	27			27		27 k€ dispo
Moving system / Scanning dipole	P2IO - 8178	21		21			Commun PA2 / PA3
PA1: Subatomic Physics		888	27	420	441	0	
Hydrogen target	?	119			119		Attente ANR
Reaction chamber	P2IO - 8176	52		52			27 k€ dispo
Detector system	SESAME	395	27	368			395 k€
Beam Energy Measurement	?	105			105		Attente ANR
Energy compressor system	?	217			217		Attente ANR
PA3: Detectors R&D		125	0	0	93	32	
R&D and Beam Characterisation	SESAME	29			18	11	Translateur inclus dans radiobio (50-21)
Detector Instrumentation	SESAME	40			40		50 k€
Acquisition System	P2IO - 8178	56			35	21	56 k€ dispo (35 + 21 translateur inclus)
PA4: Accelerator		1072	515	155	333	69	
Klystron	P2IO 8180	155	155				285 k€ dispo
Modulator	?	150	100	35	7	8	+ 100 k€ labos
RF lines	P2IO 8179-8180	100		100			
RF Gun	P2IO 8179-8180	20	20				
Laser		0					
Vacuum	P2IO+SESAME	40		20	20		
Linac RF	SESAME	220	220				
Beam lines	SESAME	300			252	48	
Diagnostic linac (BPM,YAG,DAQ)	P2IO 8179-8180	67	20		47		
Diagnostic beam line	P2IO+SESAME	20			7	13	
TOTAL		2160	542	596	921	101	
Dépenses sur P2IO		514	222	176	116	0	
Dépenses prévues sur SESAME		1070	220	420	337	93	
Montant justifié par P2IO			111	88	58	0	
Montant des factures pour justif (autres financ.)			218	664	558	186	
Dépenses Labo		100	100	0	0	0	
Non financés		476	0	0	468	8	

Current state of the art

- **Existing structure, some Issues:**
  - Locked and radio-protected 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