Projet Emblématique

PRAE:
Platform for Research and Applications with Electrons

Imagerie et Modélisation en Neurobiologie et Cancérologie

Institut de Physique Nucléaire

Laboratoire de l'Accélérateur Linéaire

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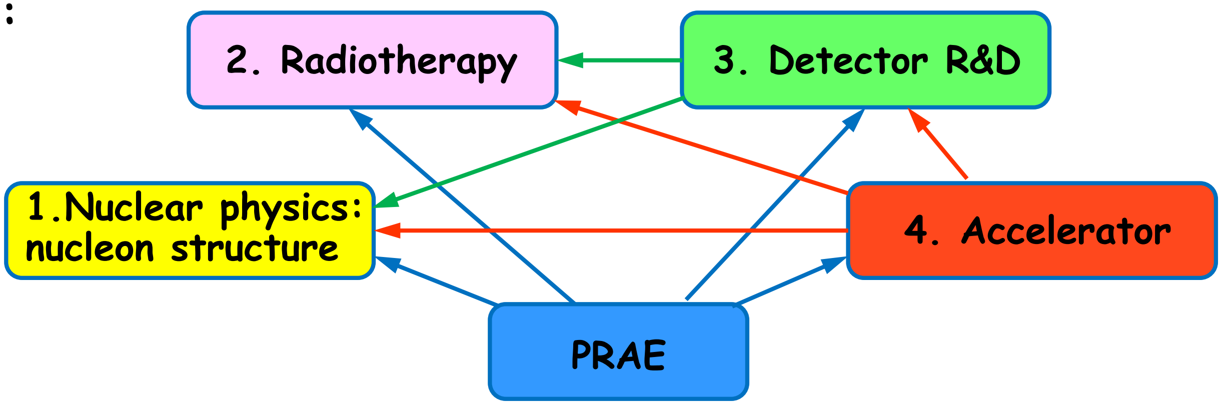
Sergey Barsuk on behalf of the PRAE team

Project presentation to the Scientific Council of P2IO

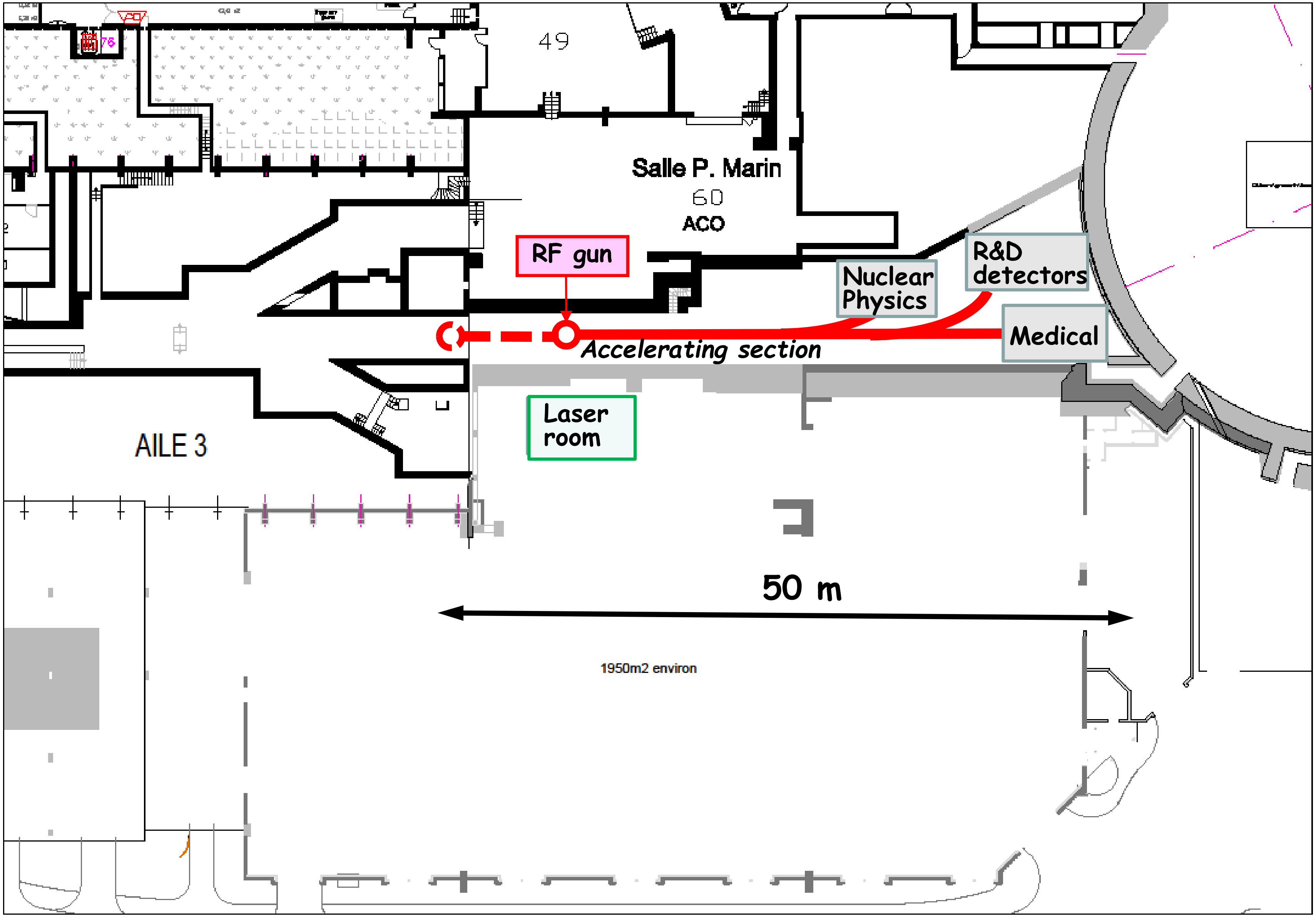
CEA – Orme des Merisiers, 07.06.16

- **PRAE: the multi-disciplinary site** based on the **high-performance electron beam** with the energy of **70 MeV** (intermediate PRAE version) and **140 MeV** (designed PRAE version). Infrastructure and PRAE design allows an upgrade to 300 MeV.
- Mutually linked **axes of PRAE:**



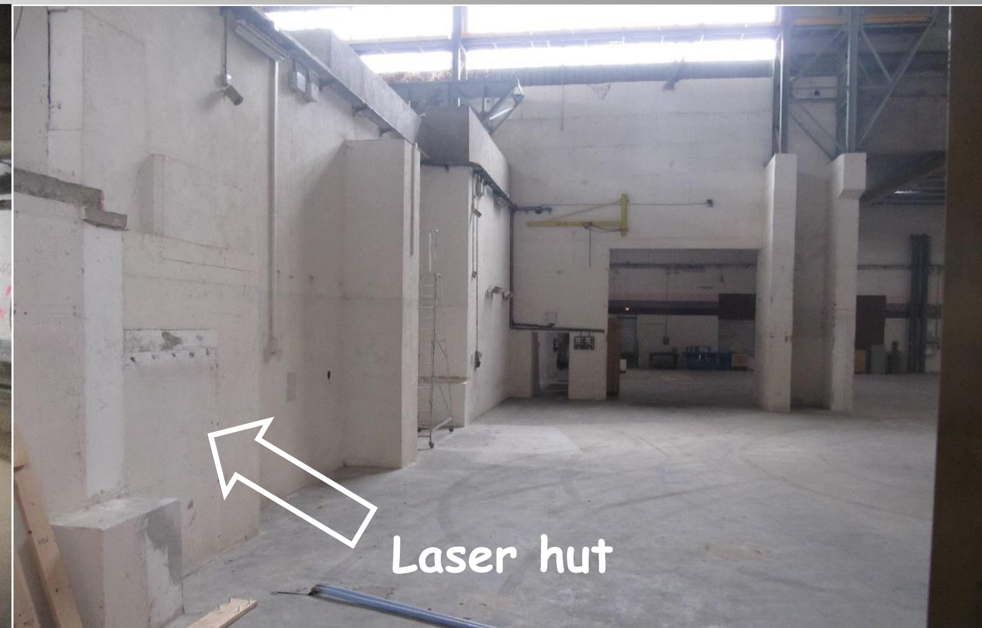
  - **Axis 4 – Accelerator: construction of the machine** (direct line + two deviated lines) to **service** other axes with the beam of required performance; **accelerator R&D**; **training**.
  - **Axis 1 – Nuclear physics/nucleon structure**: **proton charge radius**; **training**.
  - **Axis 2 – Radiotherapy:** new approaches in radiotherapy; promising for IMRT (Intensity Modulated Radiation Therapy), radiobiology studies.
  - **Axis 3 – Instrumentation R&D**: versatile instrumentation **platform; training.**
- **Transversal project.**
- **Strong complementary expertise** of the IMNC, IPN and LAL groups proposing the project.
- Re-use of the **unique site of the former Linear Accelerator** and its infrastructure.

Former site of linear accelerator at LAL



Classification waved now !

Former site of linear accelerator at LAL



- **PRAE Phase 1** ***(Essential contribution by P2IO.)***
  - **Accelerator**: 2 nC electron bunches at 50 Hz, accelerated to 50-70 MeV, **direct PRAE beam line.**
  - **Nuclear physics/nucleon structure**: optimization of the setup using simulation and tests; **tests of the target for the complete ProRad instrument; measurement of the electric form factor of the proton.**
  - **Radiotherapy**: validation of the PRAE setup, dosimetry campaign, using goniometer.
  - **Detector R&D: calibration and commissioning** of the setup. **First use by instrumentation groups.**
  - Numerous tests and validations possible with the existing PHIL, ALTO, … facilities.
  - Edition of **Technical Design Report.**

Three phases of PRAE construction

- **PRAE Phase 2**
  - **Accelerator: direct (radiotherapy platform) and two deviated beam lines** (nuclear physics and detector R&D)
  - **Nuclear physics/nucleon structure**: **nominal ProRad** experiment operation.
  - **Radiotherapy:** PRAE setup, dosimetry campaign, validation using **scanning dipole.**
  - **Detector R&D: spectrometer; routine use by instrumentation groups.**
- **PRAE Phase 3**
  - **Accelerator**: new accelerator section, **maximum planned energy 140 MeV reached.**
  - **Nuclear physics/nucleon structure**: **complementary ProRad measurements**; program extension.
  - **Radiotherapy**: **dosimetry, small animals** measurements.
  - **Detector R&D: routine use by instrumentation groups.**

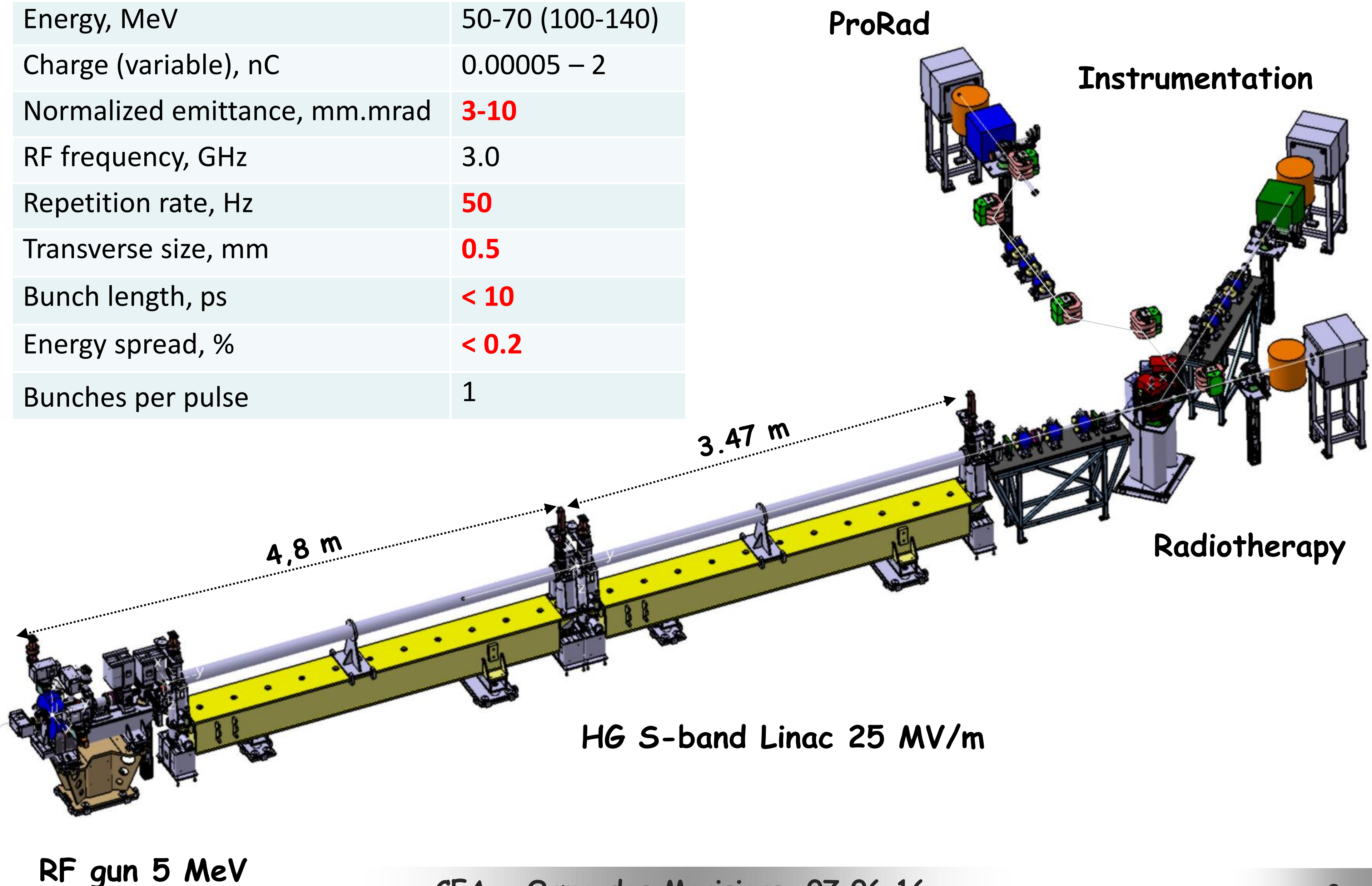
Axis 4: accelerator construction and related R&D

Coordinator: Angeles Faus-Golfe (LAL)

- *Principle goal :* ***core accelerator construction / application***
- *Other studies : R&D high-gradient RF, large intensity dynamic range BPMs, R&D on other accelerator applications*
- *Training of engineers and technical staff; Students' hands-on*

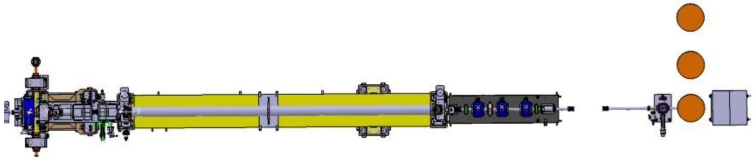
PRAE accelerator construction

Beam parameters	phase 1-2 (3)
Energy, MeV	50-70 (100-140)
Charge (variable), nC	0.00005 – 2
Normalized emittance, mm.mrad	**3-10**
RF frequency, GHz	3.0
Repetition rate, Hz	**50**
Transverse size, mm	**0.5**
Bunch length, ps	**< 10**
Energy spread, %	**< 0.2**
Bunches per pulse	1

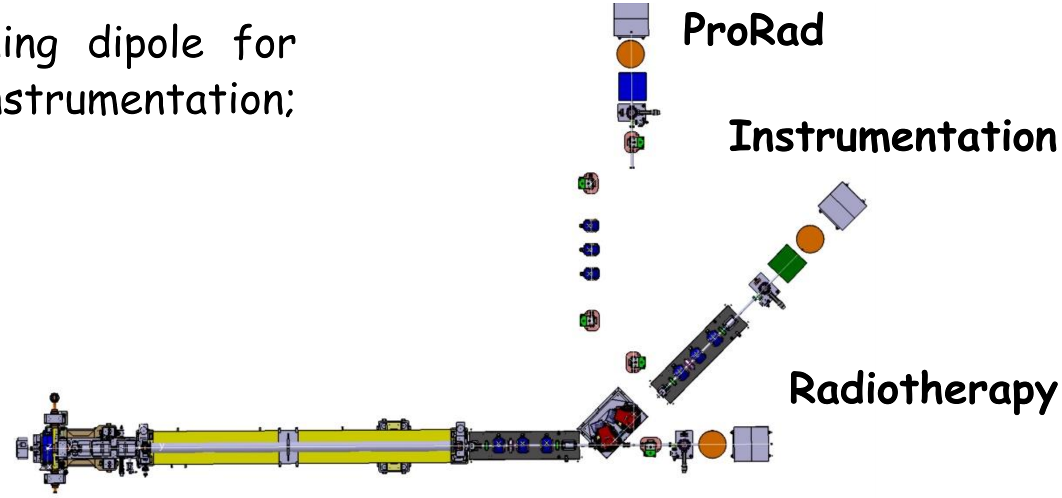


PRAE accelerator construction

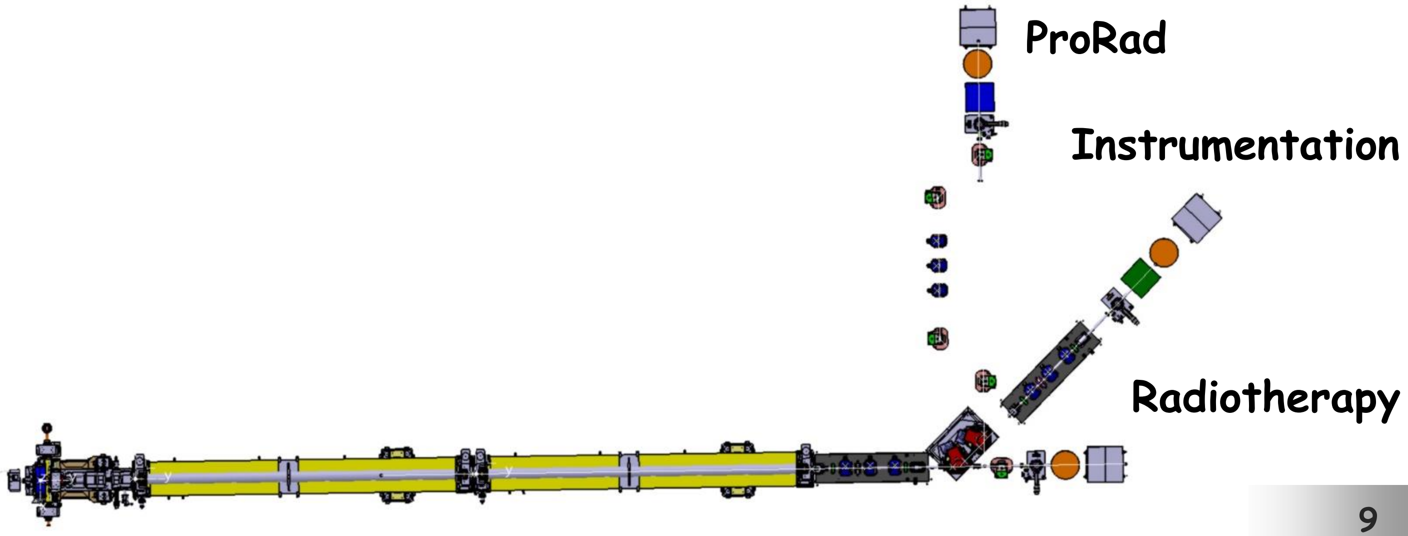
- **Phase 1:** RF gun at 50 Hz; 50-70 MeV



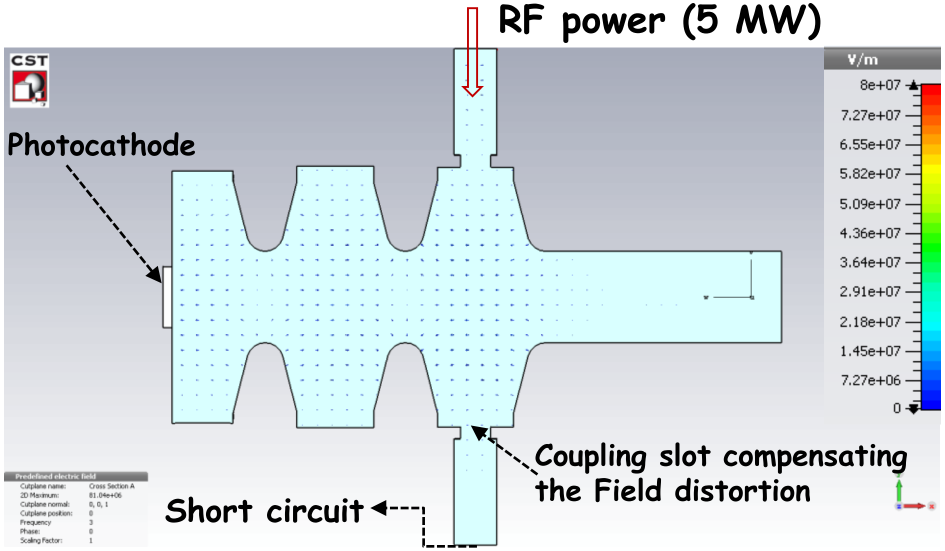
- **Phase 2:** two deviated lines; scanning dipole for Radiotherapy; spectrometer for Instrumentation; magnetic chicane for ProRad.



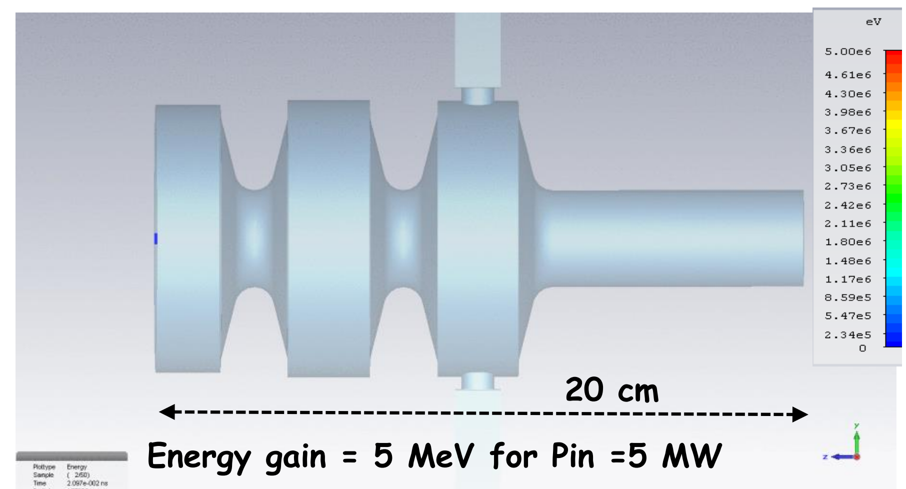
- **Phase 3:** 140 MeV



Accelerating gradient (TM_{010} _ π mode):
80 MV/m at P_{in}=5 MW



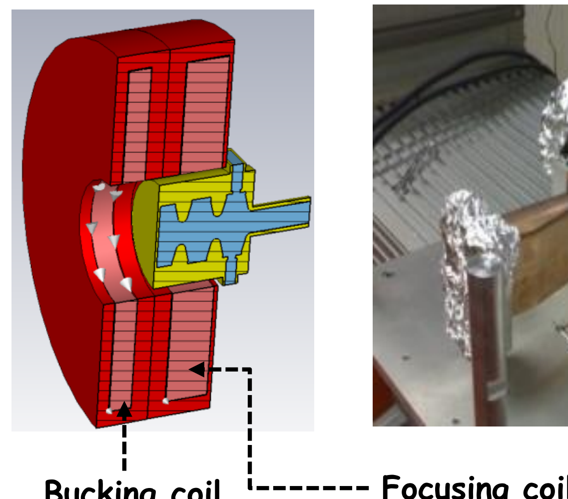
CST-Particle in cells, simulation results: Mohamed



Photoinjector specification

Operation frequency	2998,55 MHz (30°C, in vacuum)
Charge	1 nC
Laser wavelength, pulse energy	266 nm, 100 µJ
RF Gun Q and Rs	14400, 49 MΩ/m
RF Gun accelerating gradient	80 MV/m @ 5 MW
Normalized emittance (rms)	4.4 π mm mrad
Energy spread	0.4 %
Bunch length (rms)	5 ps

Gun with its coils (CST)



RF gun designed and produced at LAL

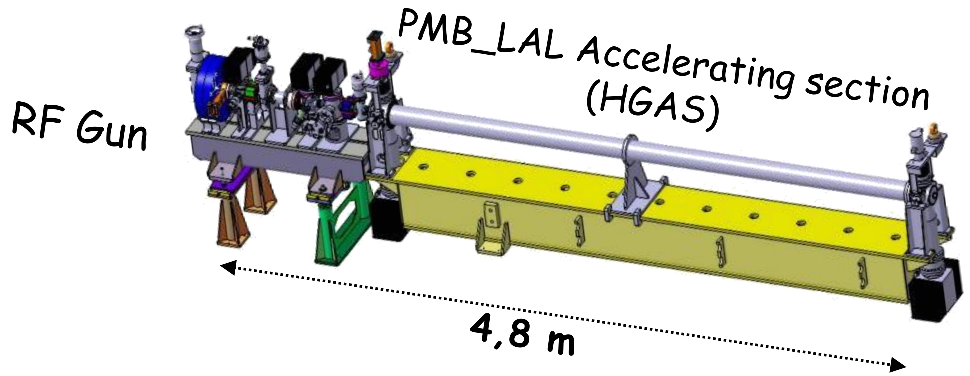
High-gradient research collaboration, LAL - PMB company

- The PRAE accelerator will profit from the high-gradient S-band accelerating structure development of the **HGAS project ("CIFFRE"** project, **collaboration with industry)**:

  Development of high-gradient S-band TW accelerating structure (HGAS)

  Project Responsible: Dr. Mohamed El Khaldi, duration: 2014 - 2018 (4 years)

- Direct application of high-gradient compact S-band electron LINAC for PRAE



HGAS Technical specification:

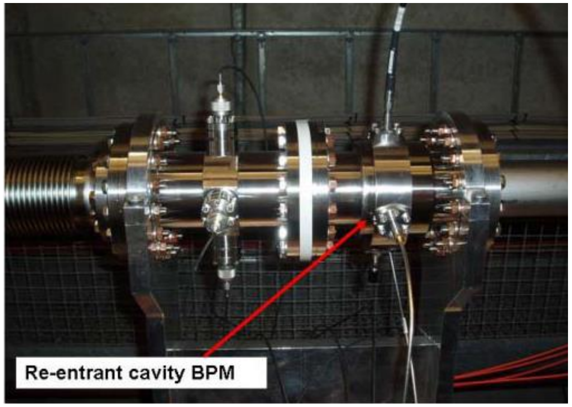
Structure	Disk-loaded
Operation mode or phase advance	$2\pi/3$
Operation Frequency	2998,55 MHz (30°C, in vacuum)
Accelerator type	Quasi constant gradient, travelling wave
Accelerating Field for an input peak power of 22 MW	25 MV/m (peak value)
Energy gain for an input peak power of 22 MW	65 MeV (only HGAS)
Quality factor Q	> 14000
Number of cells	94 + 2 coupler cells
Flange to flange length	3,47 m

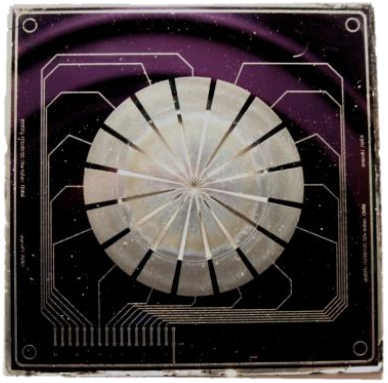
High-gradient accelerating structure development: challenges

- The major obstacle to achieve higher gradients is **RF breakdown**, limiting working power and producing irreversible surface damage.
- **Breakdown limit** depends on the RF circuit, structure geometry, and RF frequency. Also a function of the input power, pulse width, surface electric and magnetic fields and modified Poynting vector.
- **Improvements** achievable via
  - RF design optimization: optimization of the cell shape in order to maximize RF efficiency and minimize surface fields and modified pointing vector at very high accelerating gradients;
  - Fabrication process optimization: precision machining, cleaning, brazing, …
  - New materials: Copper Alloys, Tungsten, Molybdenum, … in critical areas
- **Prototypes** have been designed and are under fabrication by PMB: investigate all possible issues (RF, mechanical) and improve the machining of cells and brazing processes.

M. EL Khaldi, L. Garolfi,"RF DESIGN OF A HIGH GRADIENT S-BAND TRAVELLING WAVE ACCELERATING STRUCTURE FOR THOMX LINAC", Proceedings of IPAC2015, Richmond, VA, USA

- **Phase 1, BPMs:** large **intensity range** required (2 nC - 10 pC), studies to make a **technology choice**
  - **Re-entrant cavity type (CALIFE-CTF3**; 5 μm resolution in a ±5 mm dynamic range**)**
  - **Microstrip Metal Foil Monitors (MMD**; LIA IDEATE, prototype for PHIL test)





MMD: 16 sectors, 1 μm thick

➔ **New high-performance electron accelerator will be constructed for PRAE applications.**

➔ **Successful construction will be ensured by the expertise of participating laboratories.**

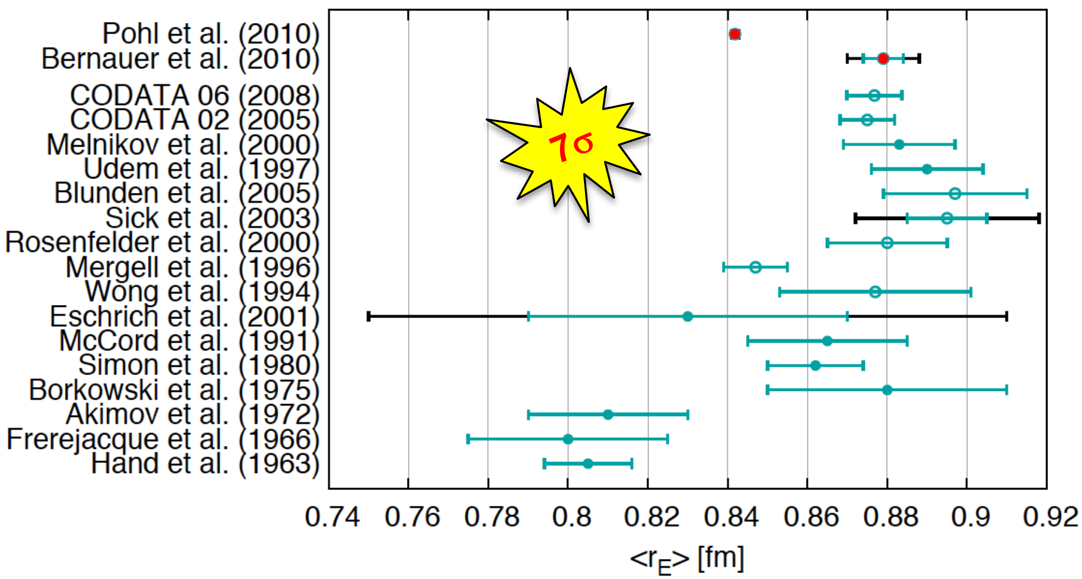
Axis 1: nuclear physics / nucleon structure

Coordinator: Eric Voutier (IPN)

- *Principle experiment :* **proton charge radius measurement, 30-70 MeV**
- *Students' hands-on*

- Determination of the proton charge radius from **muonic hydrogen Lamb shift** significantly differs from that using **electronic hydrogen Lamb shift** and **electron scattering**.

Courtesy of M. Distler



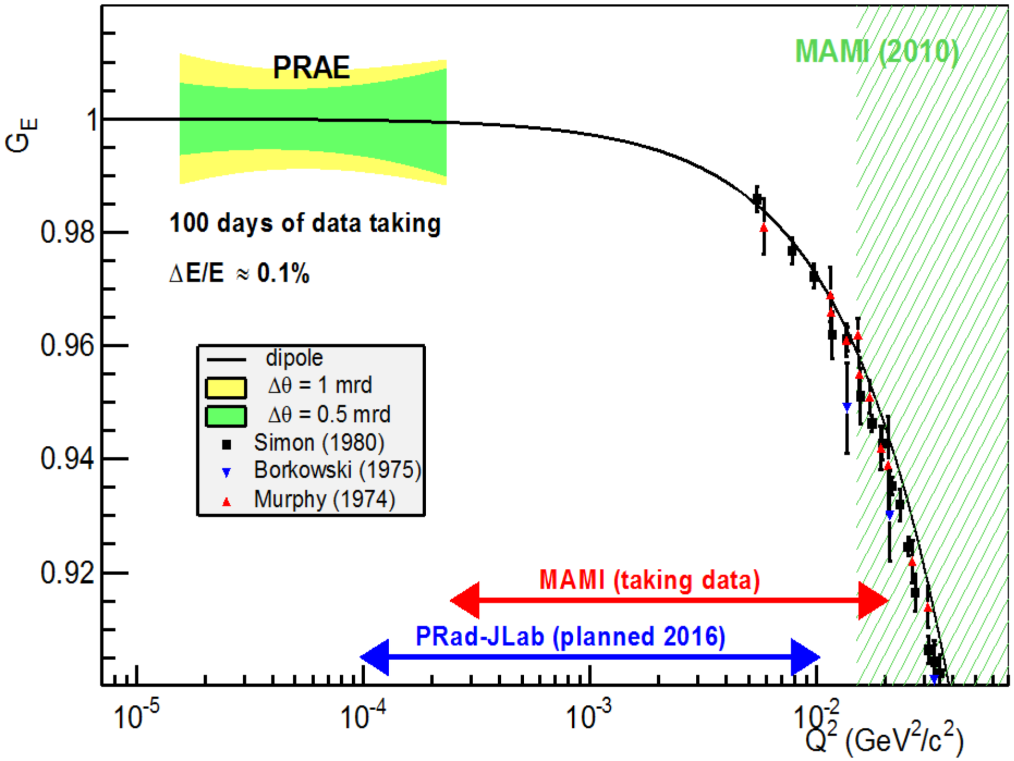
- Search for **explanations from experimental issues, theory, …** :

  Underestimated uncertainties / Bad radius determination / Lepton non-universality / New force/particles / Novel hadronic physics / … → no consensus.

- ***More data / different experiment needed !***

- The **ProRad** experiment at **PRAE** aims at accurate measurements (≤1%) of the electric form factor of the proton **$G_E(Q^2)$** at **very low** four-momentum transfer **Q^2**.

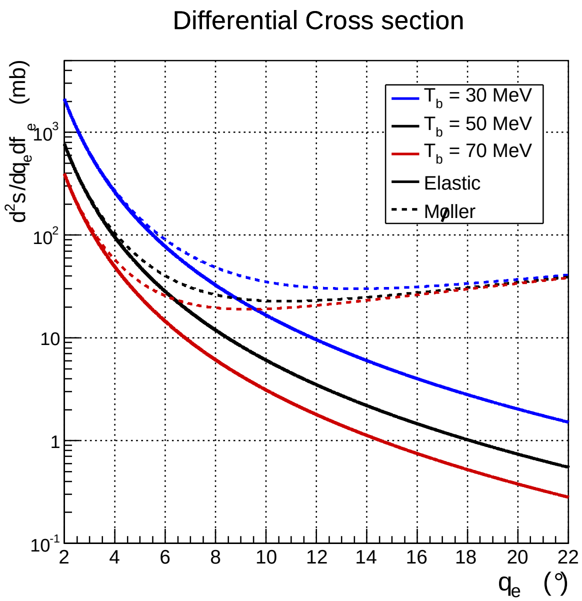
$$\frac{d^2\sigma}{d\Omega} \equiv \left.\frac{d^2\sigma}{d\Omega}\right|_{Mott} G_E\left(Q^2\right) \Rightarrow r_p^2 = -\frac{6\hbar^2}{G_E(0)} \left.\frac{\partial G_E\left(Q^2\right)}{\partial Q^2}\right|_{Q^2=0}$$

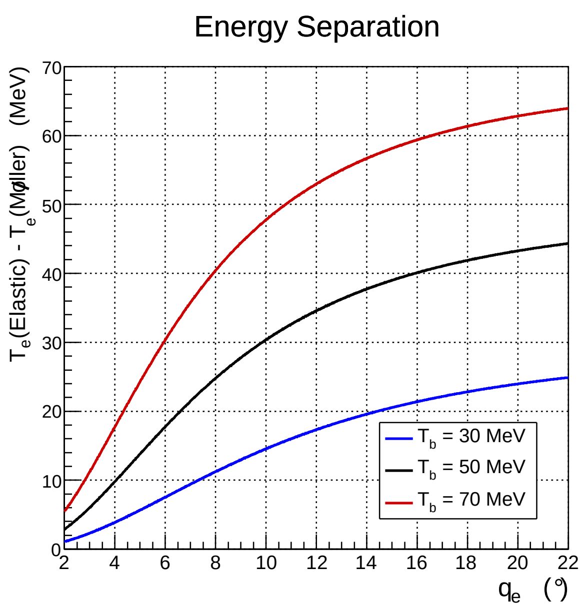


- Measurements in the **unexplored** Q^2-range **1.5×10^{-5} – 3×10^{-4} $(GeV/c^2)^2$** will **constrain** the **Q^2-dependence** of **G_E** and the **extrapolation to zero** important for the determination of the **proton charge radius**.

- Any **deviation** from **1** would indicate **genuine novel effects**.

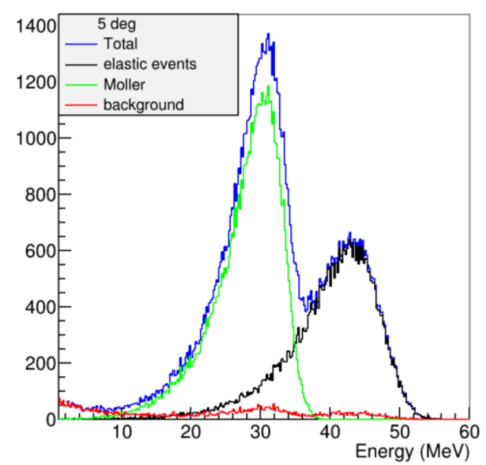
ProRad: experimental technique

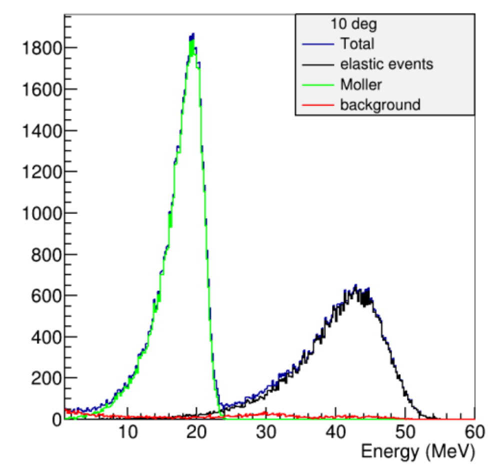




- Measurements of the **ep elastic** scattering between **5°** and **15°** (5 angle points) at 3 different beam energies, and in **absence** of any **magnetic field** and **tracking system**.

- The **energy deposit spectra** in calorimeter allow separation between **elastic** and **Møller** electrons





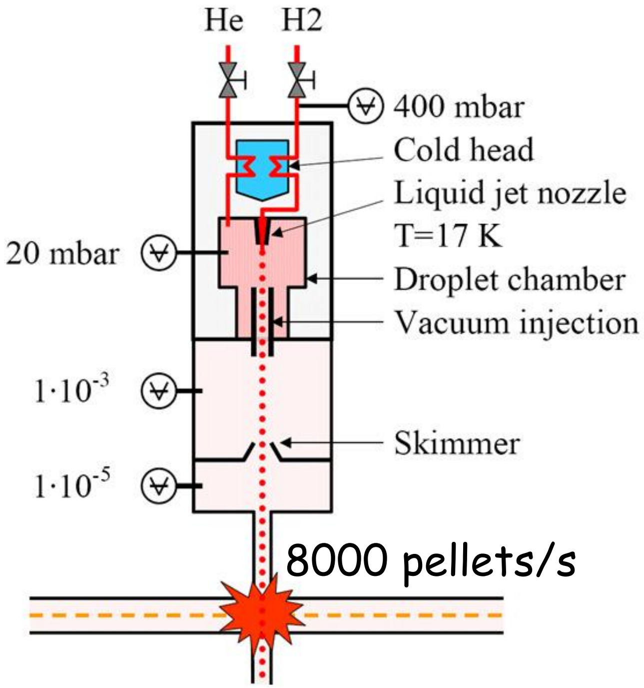
- Absolute **normalization** from **simultaneous** measurement of **ep elastic** and **ee Møller** within the **same detector** using scattered electron kinematic separation.

- Precise **beam**:

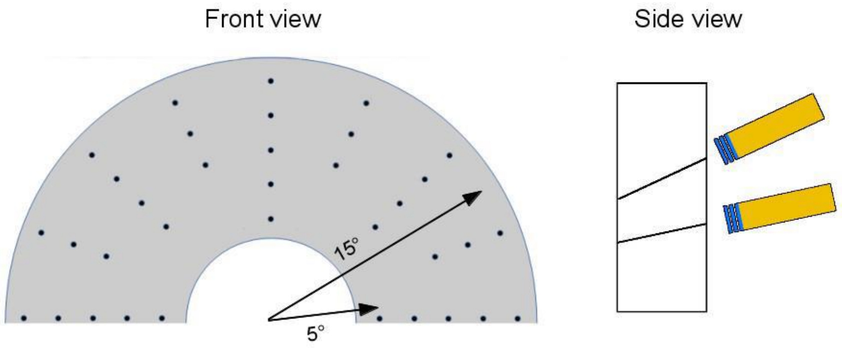
  $\Delta E/E = 10^{-3}$, $\sigma_{x,y} < 0.5$ mm, $\Delta\theta < 1$ mrad

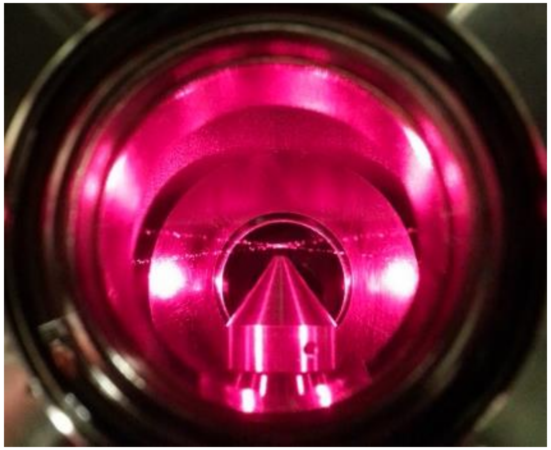
- Windowless hydrogen target
- A flux of **liquid hydrogen droplets** interact with the electron beam.

Example: WASA pellet target



- Electrons scattered at selected angles are tagged with **3 thin scintillators** and detected in a **calorimeter**.
- Mechanical definition of scattering angles via small holes machined in a thick shielding cover.





Immediate scientific impact

- Measurement of $G_E(Q^2)$ in a **unique momentum range** with marginal overlap with near future experiments.
- **New unique** and complementary magnetic field free **experimental method**.
- These results will contribute to a **more accurate** determination of the **proton radius**.

Local impact

- Creation of an attractive **pole for hadronic physics community**.
- Student and Post-doctorant training.

Further program, examples

- Measurements of $G_E(Q^2)$ at **higher energies** and/or **larger scattering angle**.
- **Fundamental physics** with **polarized beam** and **target**.

Axis 2: radiotherapy

Coordinator: Yolanda Prezado (IMNC)

- *Principal goal :* ***explore new original approaches in radiotherapy***
- *Other studies : promising for IMRT, radiobiology studies*

- Radiotherapy (RT) is one of the most frequently used methods for **cancer** treatment
- Treatment of some **radio resistant tumors, pediatric cancers** and tumors close to a delicate structure (i.e. spinal cord) is currently **limited**
- The main challenge in RT is to find **novel** approaches leading to an increase of the normal tissue resistance

Tumor control probability

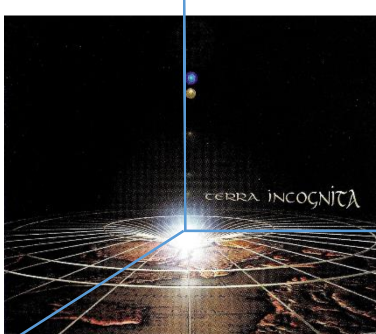
Normal tissue complication probability

Still largely unknown **how radiation physical parameters impact biological response**

Physical dose → **Biological dose**

Temporal fractionation

Standard RT



Spatial fractionation

Biological response

- Standard RT **restricted** to the few temporal and spatial schemes, dose rates, broad field sizes

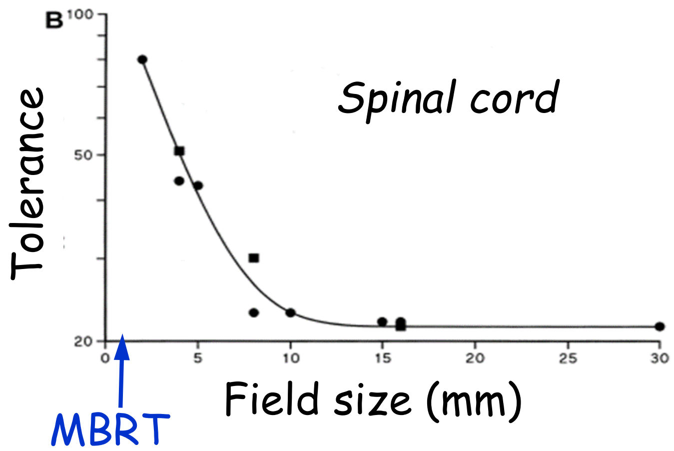
- *Mainly photons*
- *2 Gy/session, 1 session/day, 5 days/week*
- *Dose rate~ 2 Gy/min*
- *Field sizes > cm²*
- *Homogeneous dose distributions*

- Different particle types: very **high energy electrons** (VHEE)
  - At hospitals mainly photons (6-18 MV) and electrons (2-25 MeV) are used.
  - *Compared to clinical electron beams*: longer **penetration depth**; reduced **lateral scattering** (transversal widening → sparing normal tissues).
  - *Compared to photons*: **scans** possible → advantageous for image-guided energy- and intensity-modulated radiation therapy. Stanford University exploring this approach with laser sources.
  - *Compared to protons*: greater **precision** of the beam, lower accelerator **cost**; less **radioprotection** issues.
  - *Biological advantages to be established !*

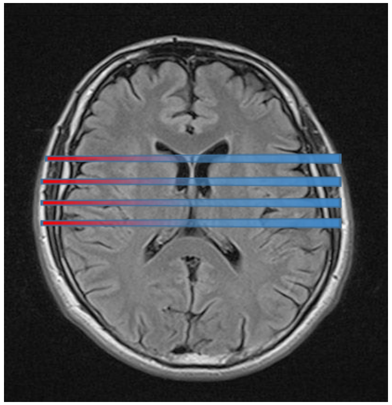
- **X-ray minibeam** radiation therapy (MBRT)

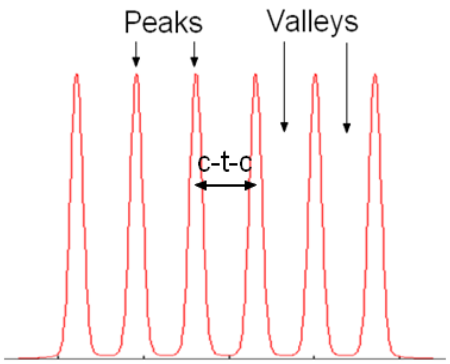
submillimetric field sizes + spatial fractionation of the dose

instead of several cm^2 *instead of homogeneous distributions*



Hopewell 2000



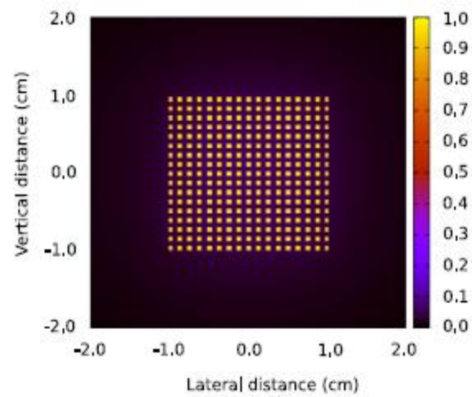


- Exponential increase of normal (rat) brain resistance.

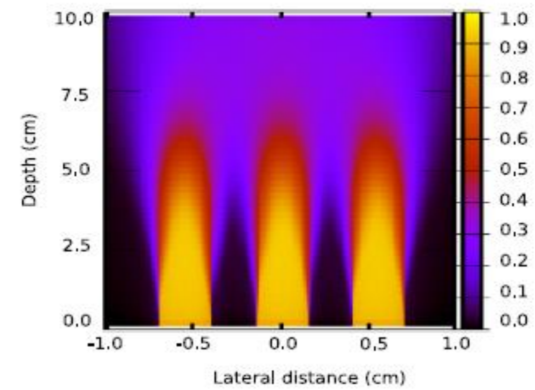
Prezado et al., Rad. Research 2015

- It opens the path for a **dose escalation in the tumor**.

- **Beams get wider in depth** due to multiple Coulomb scattering
- Normal tissues benefit from **spatial fractionation** of the dose
  while a (quasi) homogeneous dose distribution is achieved in the tumor.

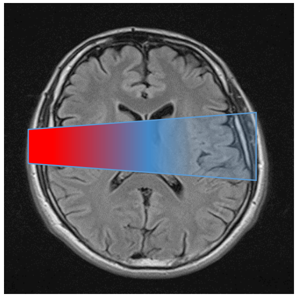


View of the grid



2D dose distributions

Very high energy electrons (VHEE)



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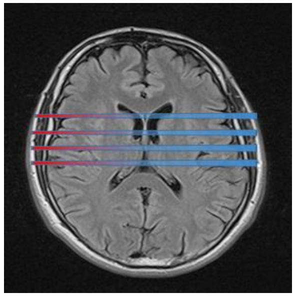
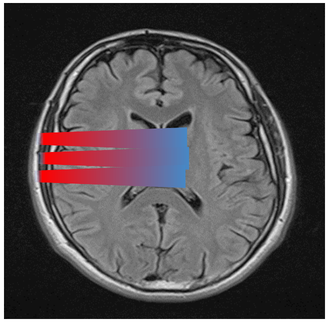
Spatial fractionation of the dose (MBRT)





Very high energy electron Grid Therapy (eHGRT)

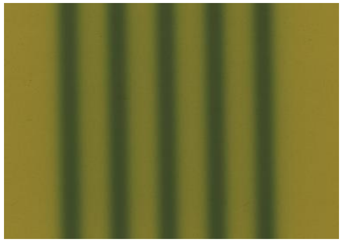
Novel approach in disrupture with standard RT

Martinez and Prezado, Med. Phys. 2015

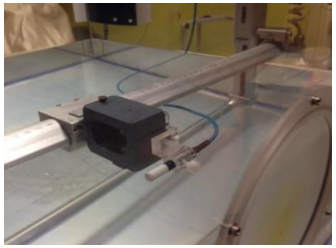
Main objectives at PRAE

- ❑ Innovative **dosimetry for very small field sizes**

<u>Experimental dosimetry</u>

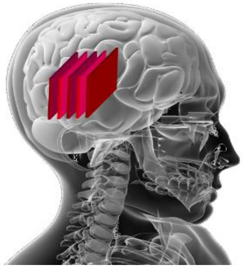


Film



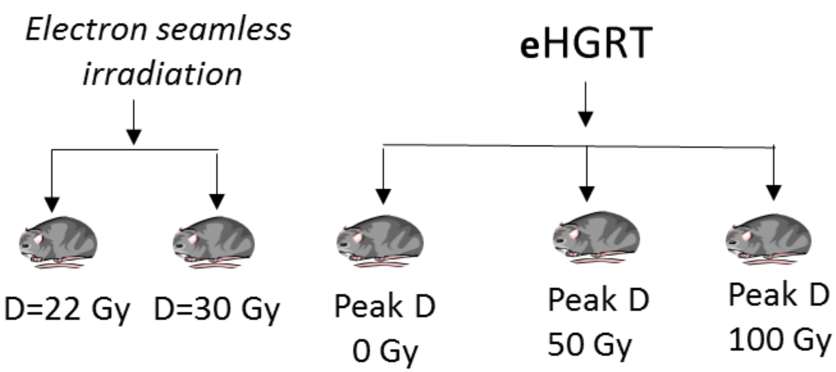
Microdiamond detector

<u>Dose calculation engine</u>



- ❑ **Confirmation of the hypothesis of high normal tissue resistance**

Whole rat brain irradiation



- ❑ Evaluation of acute and long-term effects (one year follow-up):
- ❑ ***Clinical status*** *(survival, neurological damages)*
- ❑ ***MRI follow up*** *(blood brain barrier breakdown, edemas, hemorrhages)*
- ❑ ***Histological analysis*** *(tissue integrity, demyelination, neuronal cell loss, necrosis)*

➔ **New original approach eHGRT will be studied.**

➔ **Unique R&D site for radiotherapy community.**

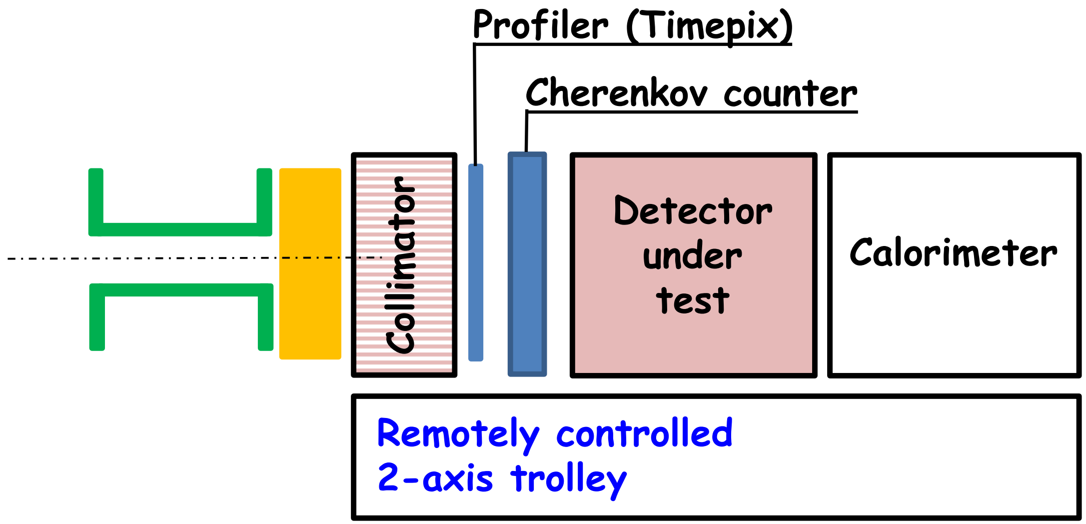
Axis 3: Instrumentation R&D

Coordinator: Bernard Genolini (IPN)

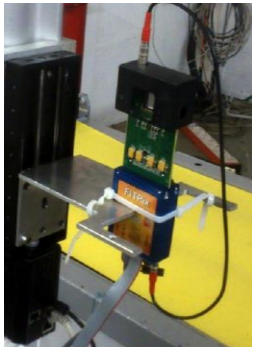
- *Principle goal is to construct versatile tool for detector R&D and tests:* **deliver calibrated beam with adjusted and known kinematics and number of electrons per sample**
- *Training of engineers and technical staff & Students' hands-on*

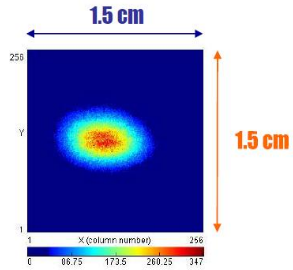
- **Fully-equipped versatile tool for precision instrumentation R&D based on high-performance electron beam**
- Excellent technical performance
  - **Timing** reference, < 10 ps bunch length
  - **Charge accuracy**, RMS < 2×10^{-3}
  - Low straggling (energy >> 1 MeV)
- High-performance, remotely controlled tools
  - **Beam position, profile and monitoring**
  - 60 digitization channels for users on NARVAL-based **data acquisition**
  - Motorized **moving table for scans**, accuracy < 500 μm
- No need to place the detectors in vacuum

Deliverables



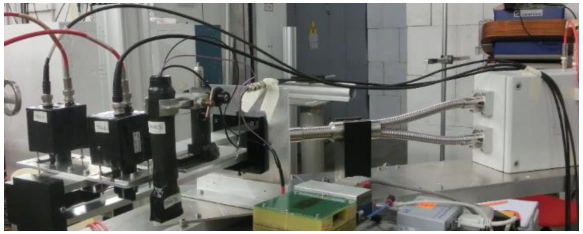
Timepix detector for precision spot measurement

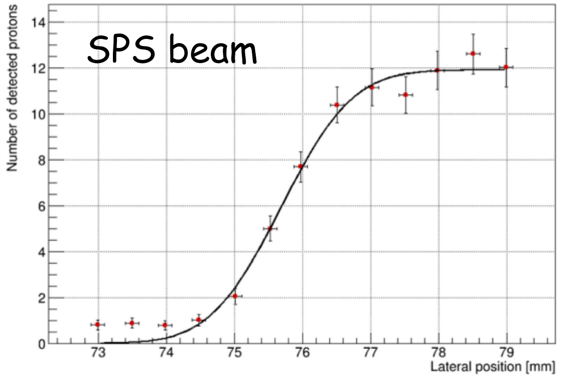




Cherenkov quartz counter for intensity monitoring

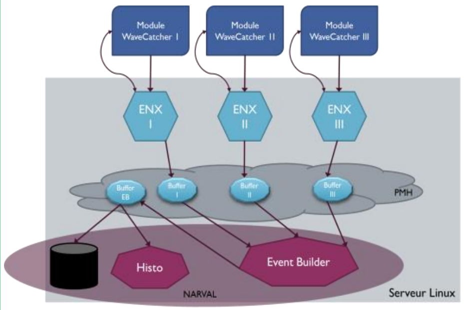
2 channel Cherenkov counters (LAL) tested at BTF (Frascati); installed in the SPS (CERN) beam pipe





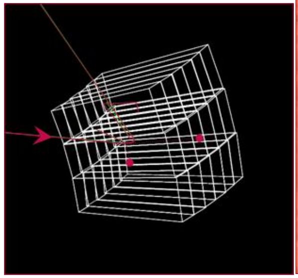
DAQ + slow control

- 60 user digitization signals (WaveCatcher)
- DCOD = NARVAL + ENX



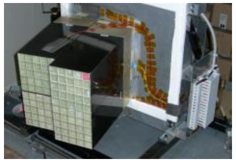
Calorimeter for energy monitoring

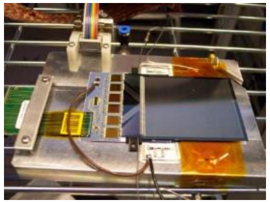
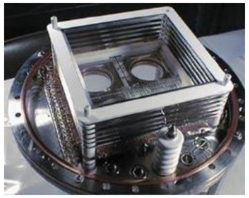
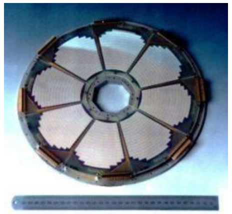
BGO scintillator crystals in compact matrix geometry



Example of a calorimeter realized at IPN

- **Local test platform** for major **instrumentation projects of P2IO and beyond**

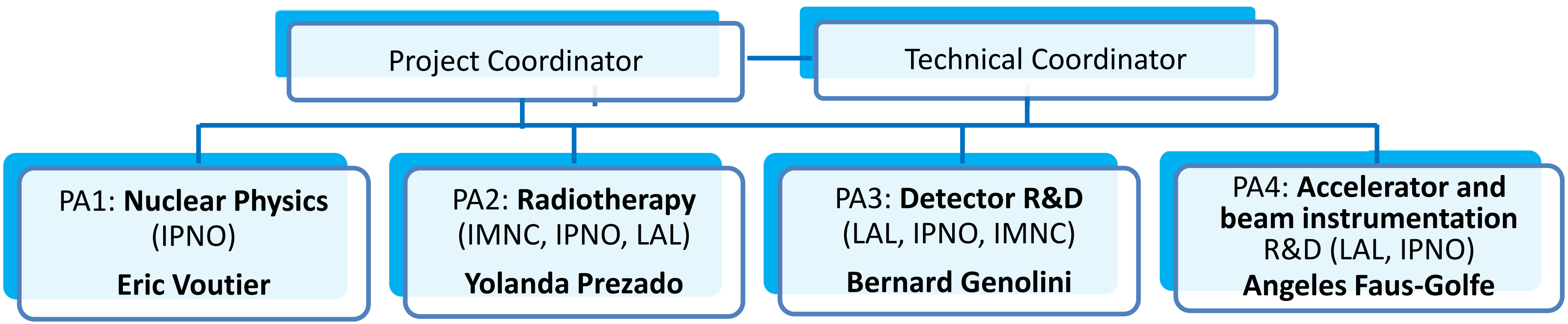


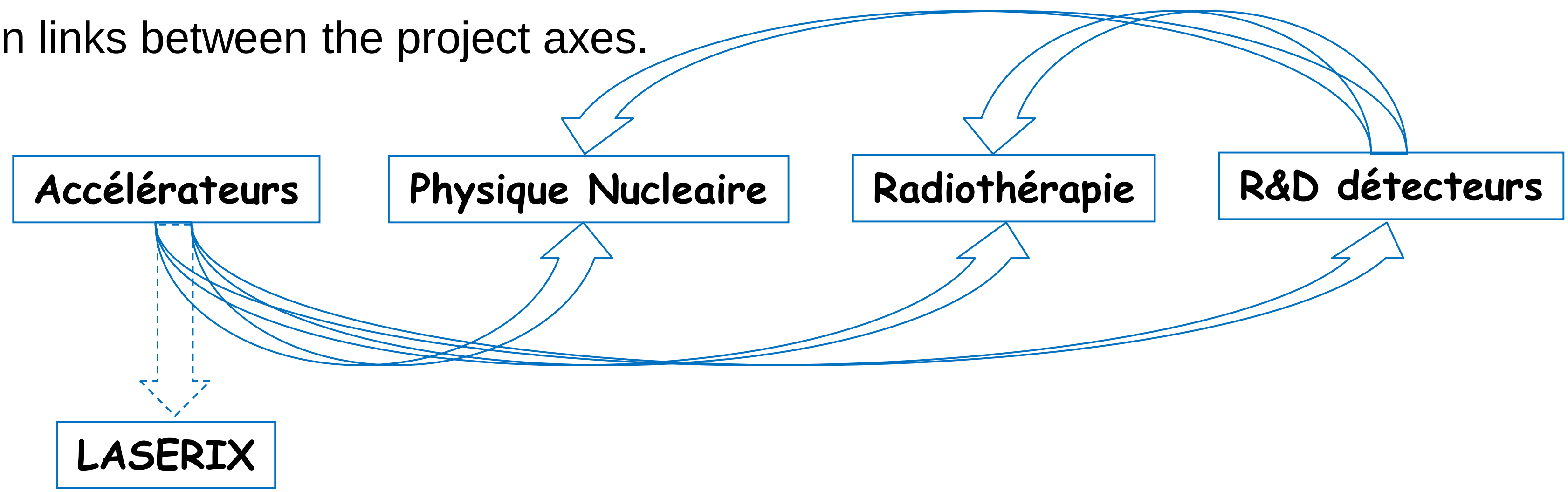
- **Science**
  - Available beam for the R&D and tests
  - Accurate scan of detectors (uniformity)
  - Time resolution
- **Feasibility**
  - Expertise of the team (CERN, JLAB, ALTO etc.)
  - Upgrade of existing productions (beam control, DAQ, signal processing)
- **Attractivity**
  - Performance
  - User-friendly: DAQ + available digitization channels
  - Students' hands-on

PRAE organization

- 4 mutually linked project axes.
- New: explicitly created task of **technical coordination.** Patricia Duchesne (IPNO) kindly accepted this responsibility.



- Main links between the project axes.



- Definition of practical **work packages** and identification of **possible bottlenecks** started in the **working groups**.

PRAE organization

- Proposed to create **Operations group** (project leader – technical coordinator – project axes responsibles) and **Steering committee** (laboratories directors, representative of IN2P3, representative(s) of P2IO – Samuel Wallon, external experts)

- Seminars in the key laboratories of the P2IO perimeter to inform and attract interested groups.
- Workshop by the end of 2016 to inform and attract external partners from industry and research.

Associated partnerships

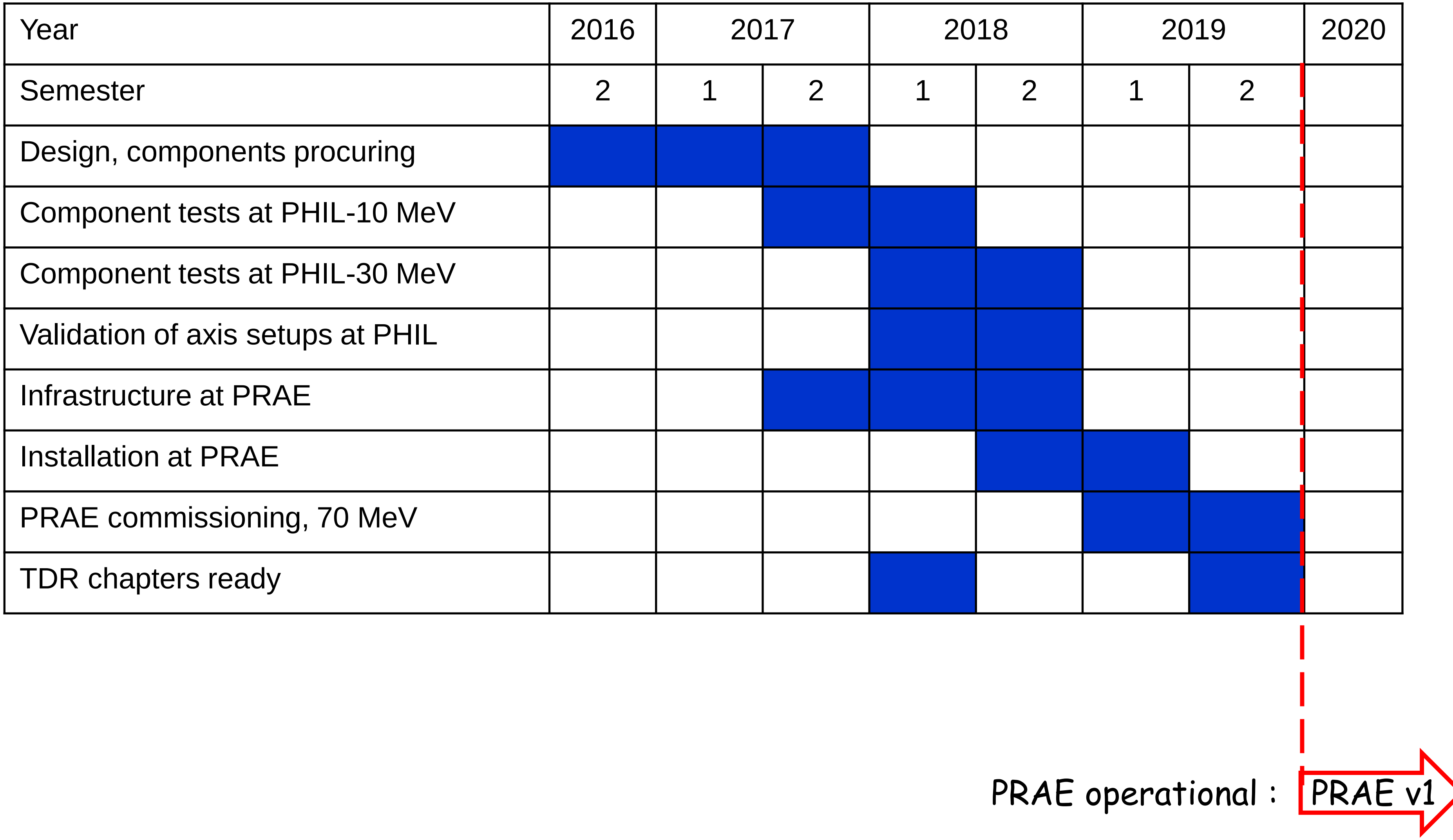
- The project will benefit from existing partnerships or those being established.

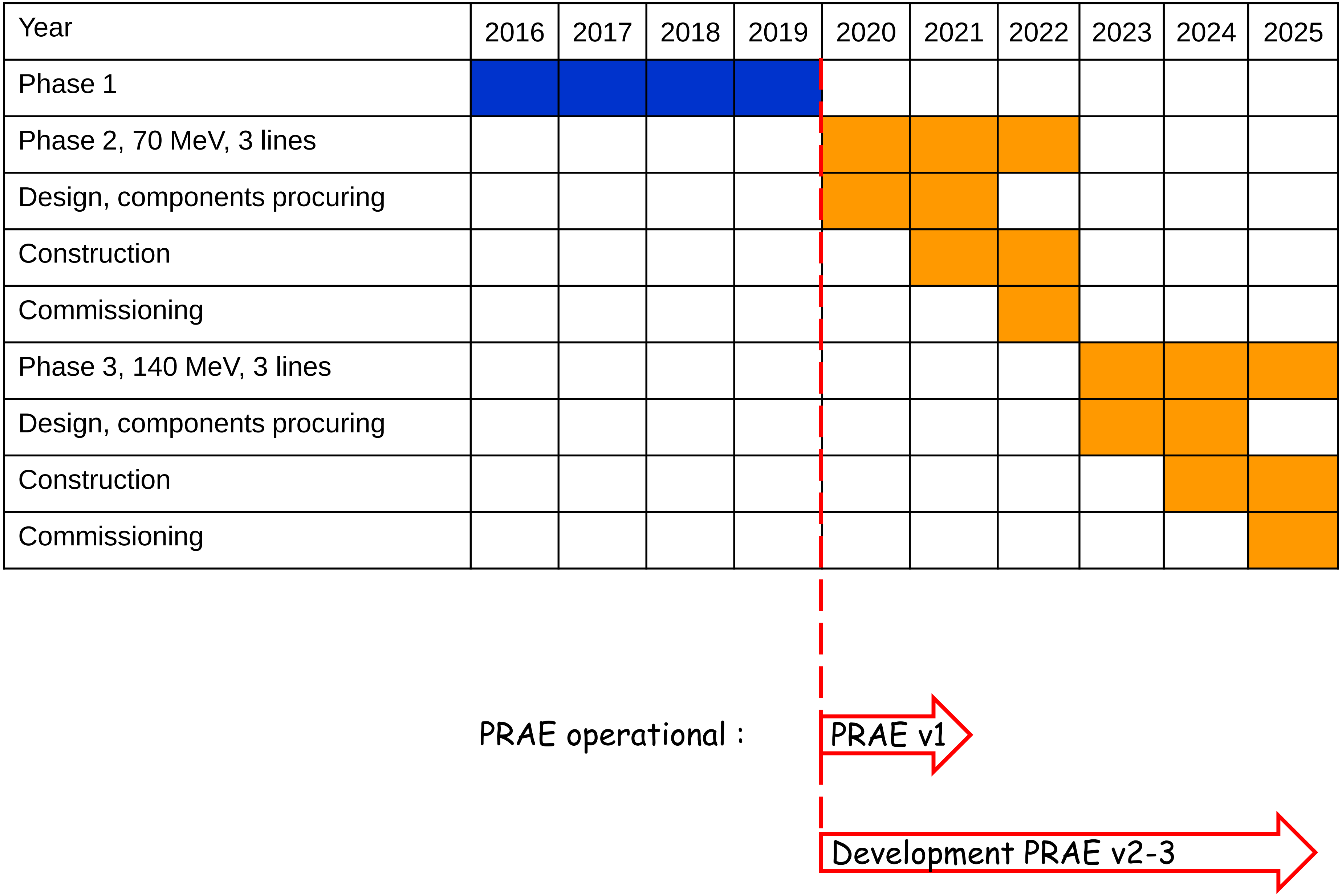
- Collaboration with **TE-MNC Technical department of CERN**: e.g. LEETECH spectrometer (also contribution from P2IO).
- Associated project is being submitted to the **SESAME** program of IdF region.
- Expressed interest for the **participation by CPO** (Centre de Protonthérapie d'Orsay).
- Possible collaboration with the **RF CLIC group at CERN.**
- Collaboration with Ukrainian groups via **LIA IDEATE.**
- Possible collaboration on the **RF technologies** (PMB, …).

- **Synergy with the ALTO, PHIL, THOMX, …** technological solutions: possible complementary production of cavities from the industrial partners; expertise, common production runs, shared equipment.

Associated partnerships, news

- Interest for full-scale participation in PRAE by **CPO**. Contribution to instrumentation of axis 2; and to axis 4.
- Interest to formally join the PRAE effort by **CSNSM**. Contribution to DAQ instrumentation for axes 1 and 3, expertise in DCOD (NARVAL + ENX), integration of the slow control (ENX), user interface, online track processing: trigger, enhanced analysis.
- Agreement with **SLAC** is being discussed. Contribution via recuperation of some accelerator components.
- Interest from the **Laserix** group as a user and contributor. Minor modification of the machine design to host Laserix electron-laser interaction program, 10 days per year. Contribution with laser and laser service.


Year
2016
2017
2018
2019
2020
Semester
2
1
2
1
2
1
2
Design, components procuring
Component tests at PHIL-10 MeV
Component tests at PHIL-30 MeV
Validation of axis setups at PHIL
Infrastructure at PRAE
Installation at PRAE
PRAE commissioning, 70 MeV
TDR chapters ready
PRAE operational :
PRAE v1


Year
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Phase 1
Phase 2, 70 MeV, 3 lines
Design, components procuring
Construction
Commissioning
Phase 3, 140 MeV, 3 lines
Design, components procuring
Construction
Commissioning
PRAE operational :
PRAE v1
Development PRAE v2-3

- **Total contribution via request P2IO** (phase 1 concerned) **: 814 kE**.

- PostDoc P2IO (2 years) + PostDoc CNRS (2 years)
- Equipment 514 kE (P2IO) + 100 kE (complementary contribution by IPNO and LAL).

- Other sources of financing the project: the **SESAME project** submitted to the IdF region.
- Infrastructure ensured via contributions by the participating laboratories.

PRAE is a unique innovative and attractive P2IO multi-disciplinary project for science, R&D and applications based on complementary IMNC – IPN – LAL expertise, in the heart of the Paris-Saclay Valley site.

- Construction of the **multi-disciplinary PRAE site – Subatomic physics, Radiotherapy, Instrumentation R&D and Accelerator** – is centered around the new high-performance electron accelerator.
- Participating **laboratories commit expertise, manpower, infrastructure and complementary funding** to complete the core of the PRAE project. Unique former Linear Accelerator protected zone will be reused.
- New original and competitive scientific program, emblematic impact expected at the P2IO, regional and national level. **Federation of the key scientific communities of P2IO around PRAE, opening to larger scientific community, industry, and education.**

Criteria of success (as requested):

- **PRAE platform, including accelerator and individual setups**, constructed and operational
- **ProRad construction**, proof of principle and first results
- **Radiotherapy construction**, dosimetric campaign accomplished, first results
- **R&D detectors** setup constructed, commissioned and ready to host users
- **Community around PRAE** progressively enlarging beyond the P2IO perimeter