Projet Emblématique

Programme SESAME

PRAE: Platform for Research and Applications with Electrons

Imagerie et Modélisation en Neurobiologie et Cancérologie	Institut de Physique Nucléaire	Laboratoire de l'Accélérateur Linéaire

Extended PRAE collaboration

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The PRAE project

- **PRAE: multi-disciplinary site** based on **electron beam** with energy of **70 MeV** and **140 MeV** (PRAE upgrade). Infrastructure and PRAE design allows an upgrade to 300 MeV
- Program: **Nuclear physics**/nucleon structure; new approaches in **Radiobiology**; **Instrumentation**; based on a high-performance electron linear **Accelerator**
- Re-use of **unique site of the former Linear Accelerator** and its infrastructure
- Total cost: 3ME
- **Start of the operation foreseen in 2021**
- Ultimate **ambitions**:
  - Decisive measurement in relation with the **proton charge radius puzzle**
  - Validated **very high energy electron** (VHEE) therapy and **grid-therapy** approaches; versatile open **Radiobiology platform including in vivo studies**
  - **Local Test Beam instrumentation platform** for HEP and Nuclear physics programs
  - Synergy with **industrial applications**
  - Strong **educational component**

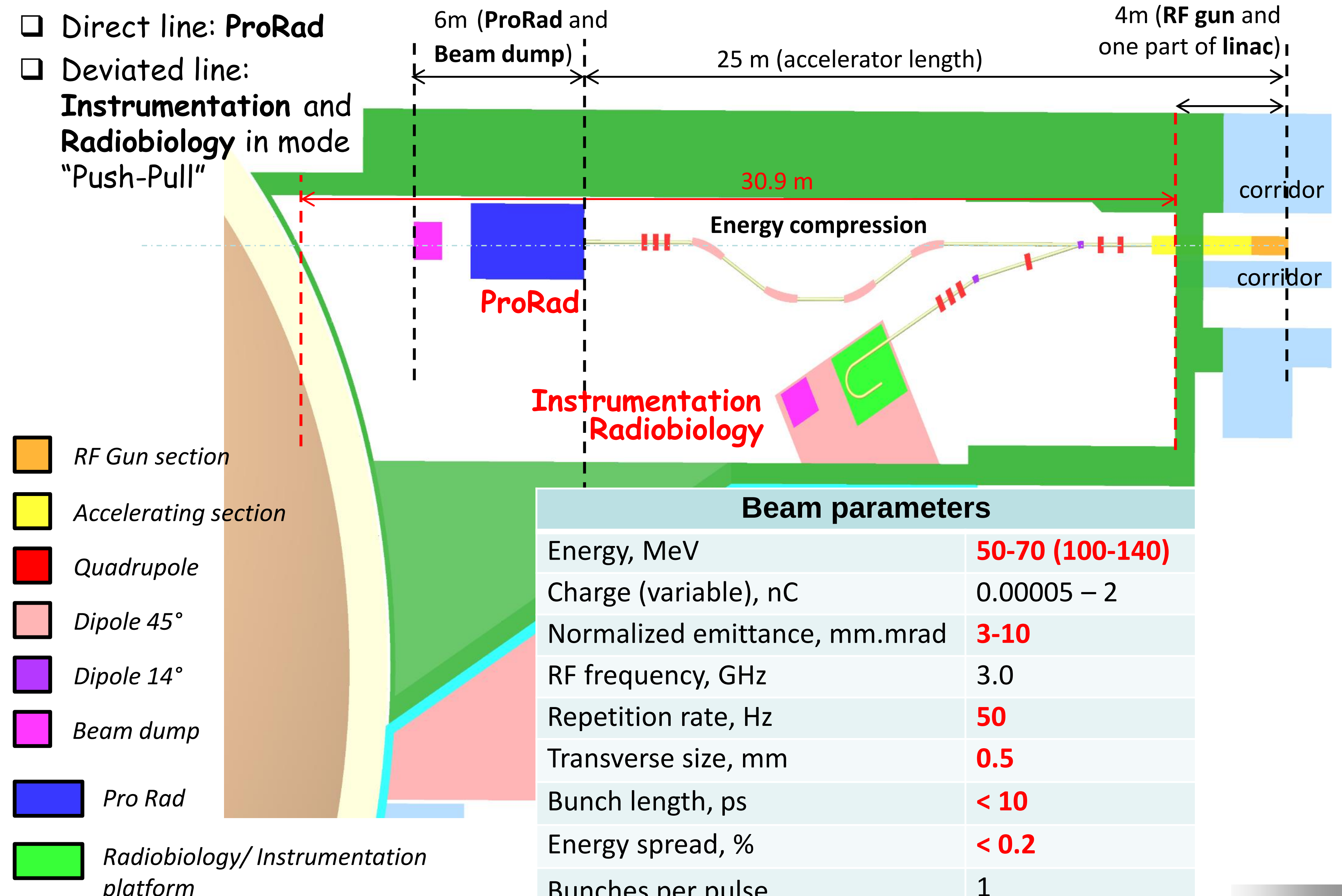
PRAE accelerator

Coordinator: Angeles Faus-Golfe

- Offer PRAE: **R&D accelerator, Applications of electron beam including Artificial intelligence, Internships and Training**
- Lecture on **Artificial Intelligence and Particle Accelerators by Mathieu Debongnie (ACS, LPSC)**
- Accelerator technical session: October 8, 9h-12h.

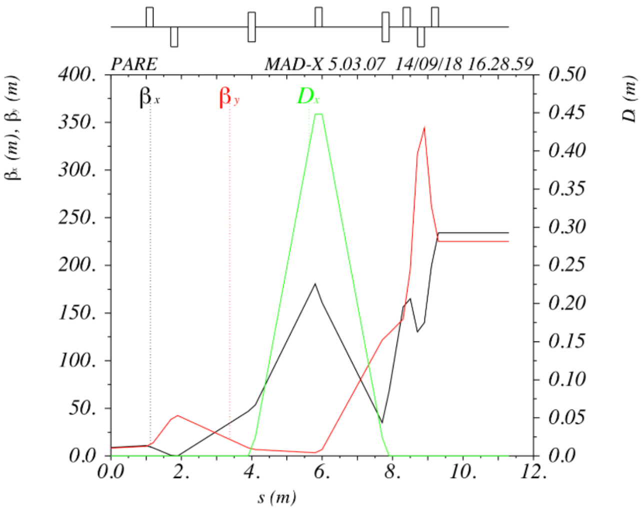
PRAE accelerator

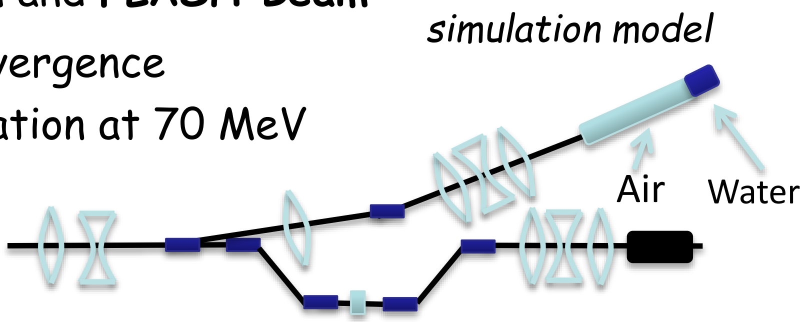
- Direct line: **ProRad**
- Deviated line: **Instrumentation** and **Radiobiology** in mode "Push-Pull"



Beam parameters	
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

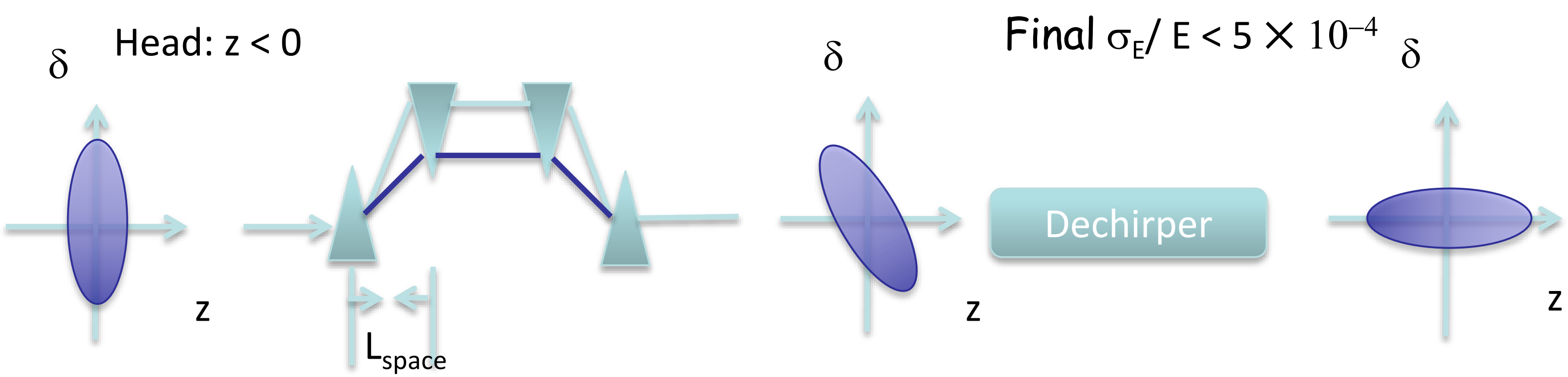
- **Radiobiology**, two operation modes: **Mini Beam** and **FLASH Beam**
- **Mini Beam**: $\sigma_{x,y}$ = 200 - 500 μm at target; low divergence
- Achieved with 140 MeV beam, technique validation at 70 MeV





- **FLASH beam**:
  - $\sigma_{x,y}$ = 10 mm ✕ 10 mm , Δt = 100 ms
  - $\sigma_{x,y}$ = 26 mm ✕ 18 mm , Δt = 500 ms
- Smaller beam size fully exploitable; possibly additional defocusing for larger beam size

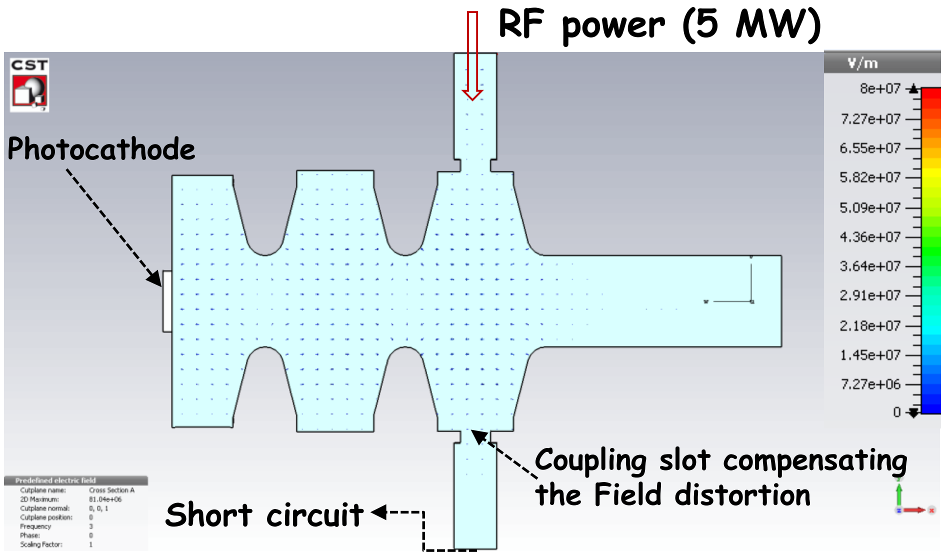
- **ProRad**: **Beam Energy Compression** and **Energy Measurement**



- Off-crest beam with passive dechirper

RF gun

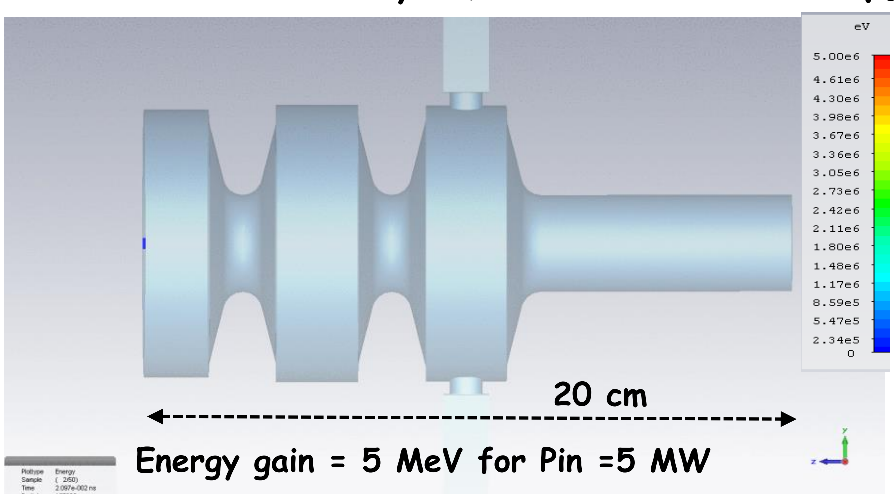
- Based on ThomX RF gun, designed and produced at LAL
- **Accelerating gradient** (TM_{010} _ π mode): 80 MV/m at P_{in}=5 MW



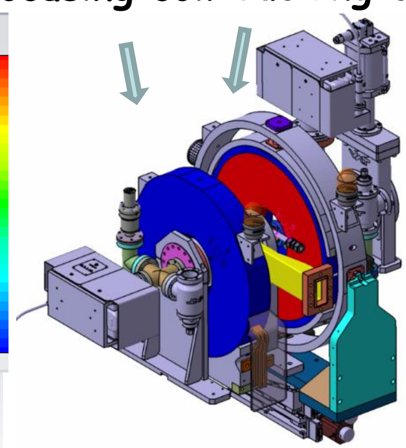
Photoinjector specification

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

CST-Particle in cells, simulation results



focusing coil bucking coil



- **Fabrication started**

- **RF powering: klystron** from **CPI**, delivery in 10/2019;
  modulators recuperated from SLAC, delivery in 12/2018

Communications & Power Industries
microwave power products division

- **High-gradient linac:** TW S-Band structures from **RI**, delivery in 10/2019

research instruments

- **Beam optics:** dipole and quadrupole magnets, **recuperation from CERN, design for Energy Compression System**

- **Beam diagnostics: inductive BPMs** recuperated from CERN, tests at IPNO in collaboration with BI-CERN

Nuclear physics / nucleon structure

Coordinator: Eric Voutier

- Offer PRAE: **Contribution to resolving the proton charge radius puzzle + complementary programme on subatomic physics, Deeply cooled liquid target technologies, Internships and Training**
- Lecture **How large is a proton ?**
  by Randolf Pohl (Maintz University)
- Subatomic physics session: October 9, 14h-17h.

❑ Determination of the proton charge radius from

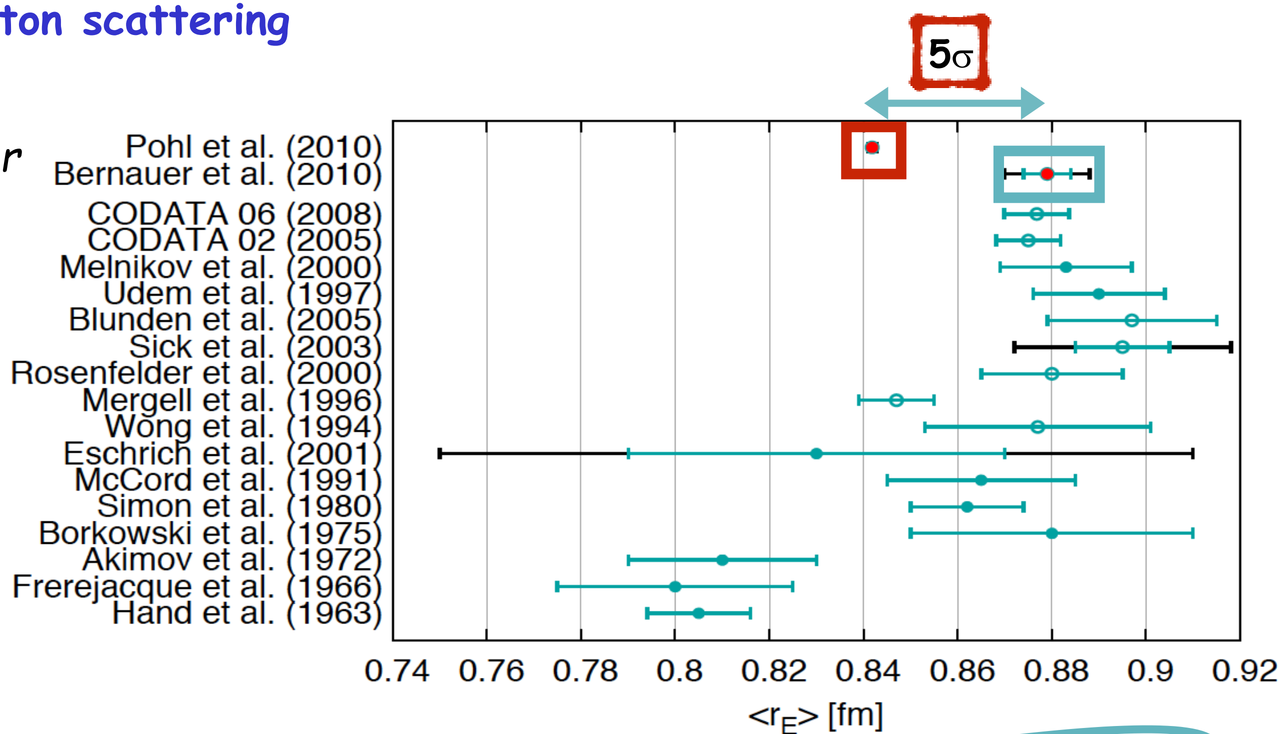
muonic hydrogen Lamb shift 2S → 2P — R. Pohl et al. Nat. 466 (2010) 213

significantly differs from that using

electronic hydrogen Lamb shift — J.C. Bernauer et al. PRL 105 (2010) 242001

and **electron-proton scattering**

*The **proton** looks smaller to **muons** than to **electrons**.*



$r_p = 0.84184 \pm 0.00067$ fm

Direct measurement

(10 times more precise)

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

$r_p = 0.87900 \pm 0.00800$ fm

Indirect measurement

(extrapolation of FF data to $Q^2 = 0$)

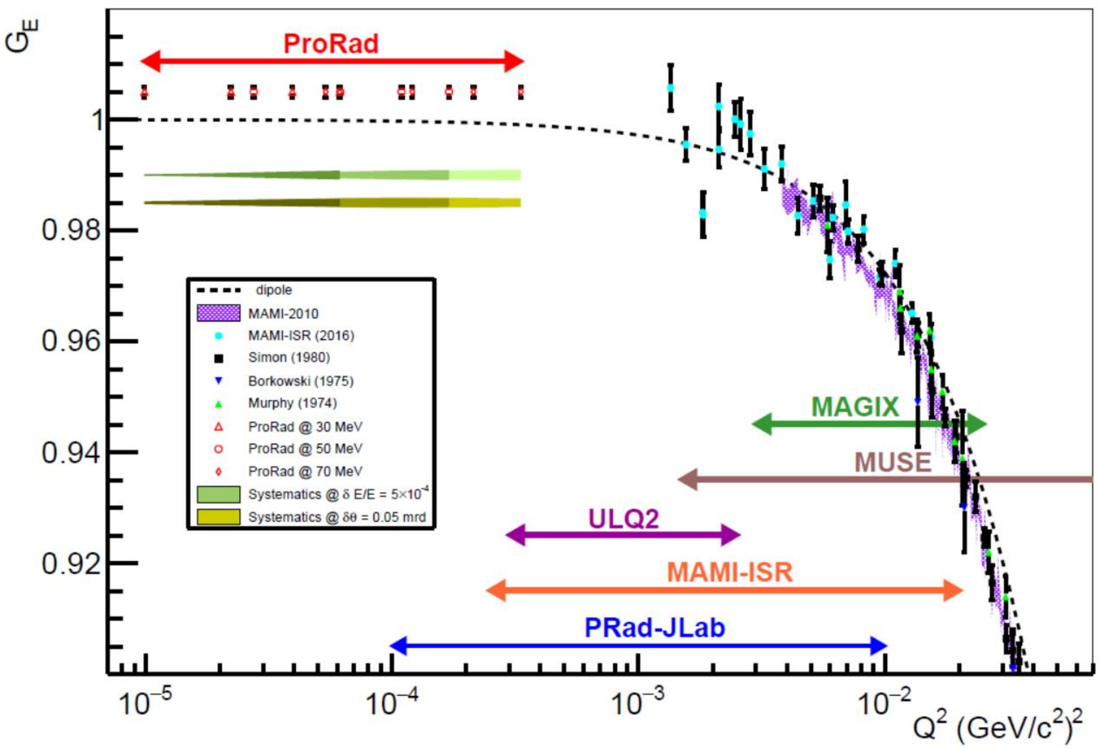
❑ **Explanations from experimental issues, theory description, new physics, …**

Platform for Research and Applications with Electrons

- The **ProRad** experiment at **PRAE** aims at accurate measurements (**0.1%**) of the electric form factor of the proton $G_E(Q^2)$ at **very low** four-momentum transfer Q^2.

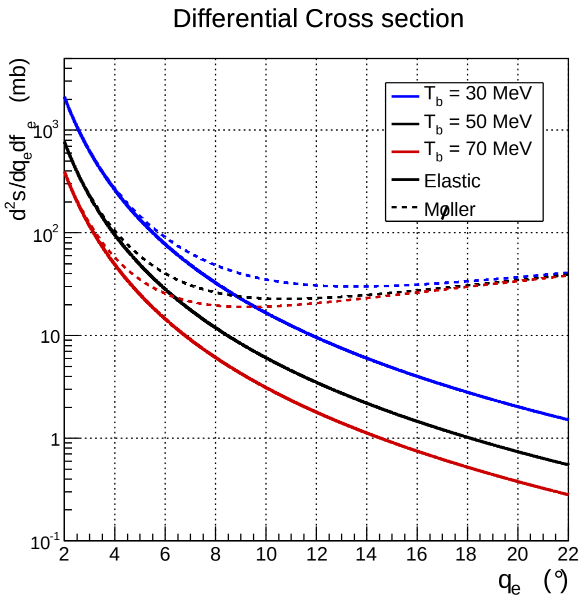
$$\frac{d^2\sigma}{d\Omega} \equiv \frac{d^2\sigma}{d\Omega}\bigg|_{Mott} G_E\left(Q^2\right) \Rightarrow r_p^2 = -\frac{6\hbar^2}{G_E(0)} \frac{\partial G_E\left(Q^2\right)}{\partial Q^2}\bigg|_{Q^2=0}$$

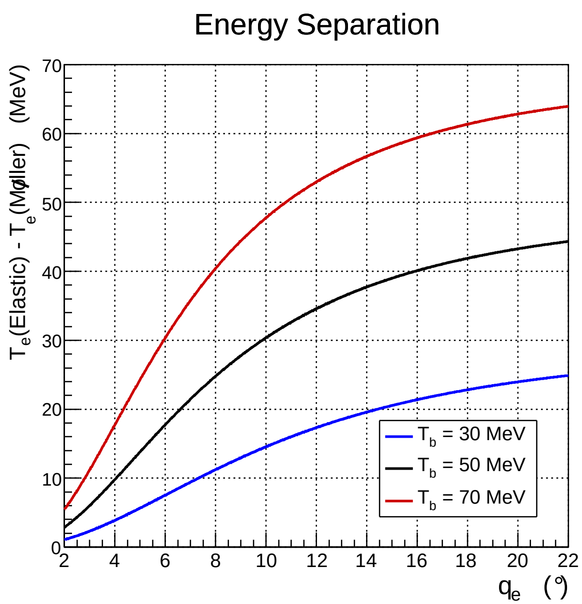
A linear region in the FF: extrapolation with no dependence on non-linearities



- 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**.

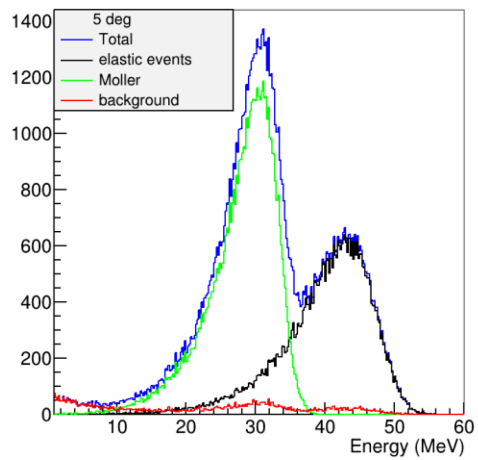
- Any **deviation** from **1** would indicate **genuine novel effects**.

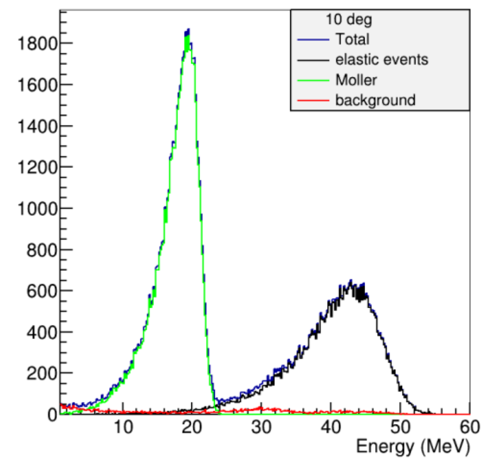




- Measurements of the **ep elastic** scattering between **5°** and **15°** (4 angle points) at 3 different beam energies, and in **absence** of any **magnetic field**

- 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. Measure ratio to 0.1%

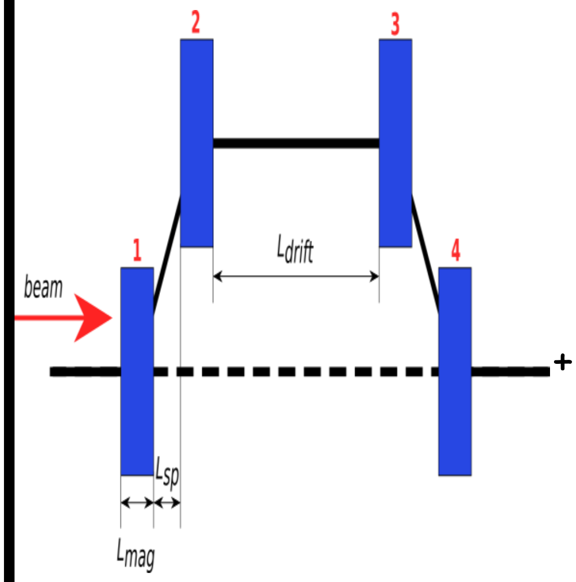
- Precise **beam**:
  $\Delta E/E = 5 \times 10^{-4}$, $\sigma_{x,y}$ < 0.5 mm, $\Delta\theta$ < 0.05 mrad

and Applications with Electrons

- High precision beam: **reduced energy dispersion**
- Precise **knowledge of the beam energy**

$$E = \frac{c}{\theta}\int Bdl = \frac{c}{\theta} I_B$$

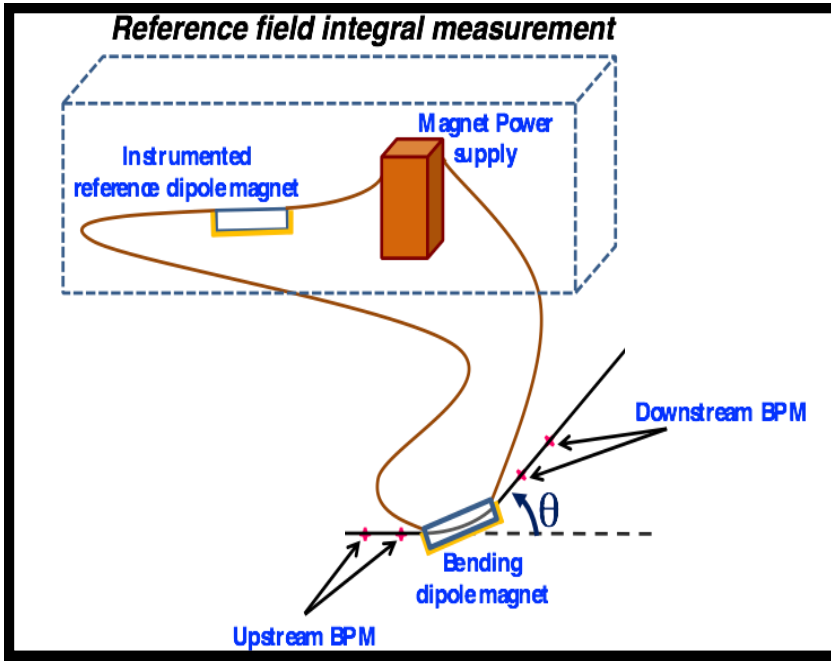
Energy compression



Association with a **dechirping Wakefield structure**

+

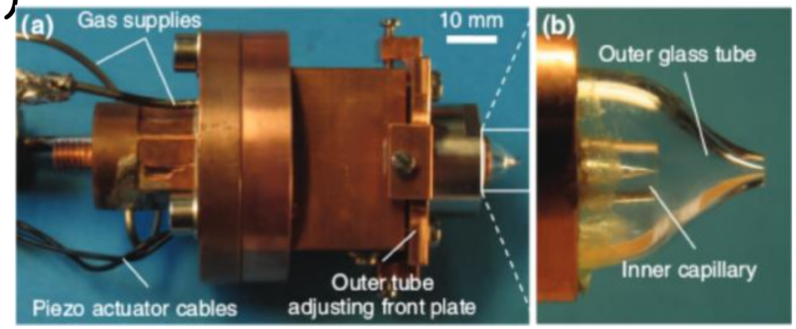
Beam energy measurement



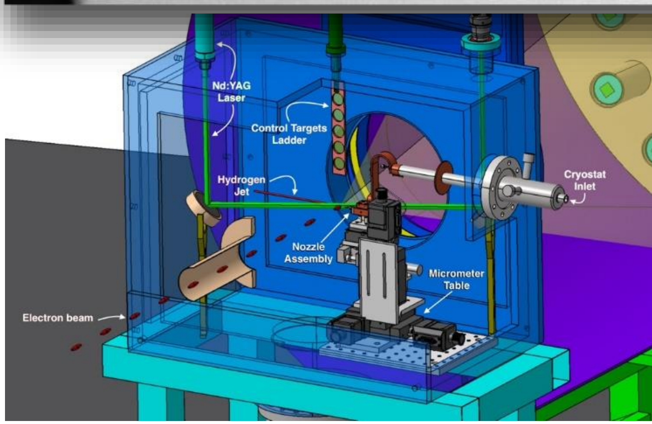
$$\frac{\delta I_B}{I_B} = \frac{\delta\theta}{\theta} = 2\times 10^{-4}$$

ProRad: measure electron scattering on Hydrogen target

- **Hydrogen target**: 15 μm diameter **solid wire** from ultra cold liquid technology (Frankfurt am Main U)

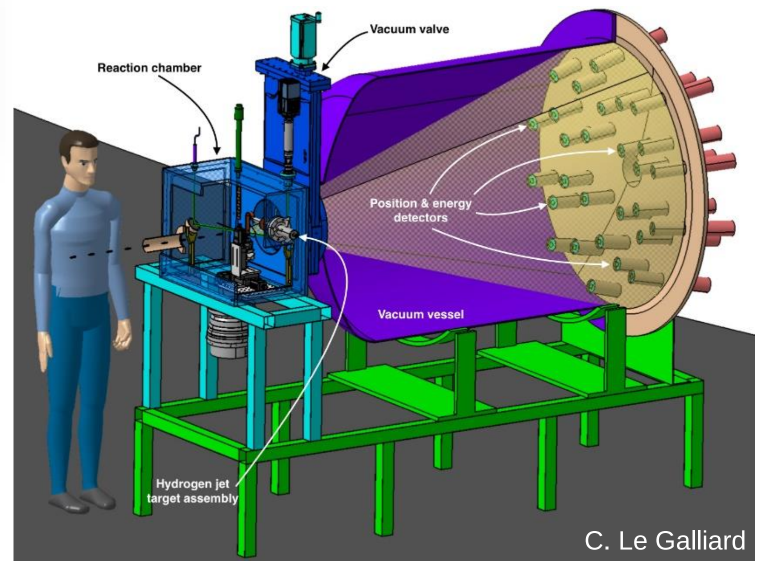


R.A. Costa Fraga et al. Rev. Sci, Inst. 83 (2012) 025102



- **Detector cell**: two planes of fibers readout by SiPM to **measure position**; BGO crystal for **energy measurement**

Reaction chamber with target assembly



- Bi-national ANR proposal with Frankfurt U

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- **Fully defined experiment, challenging measurements**

Radiobiology

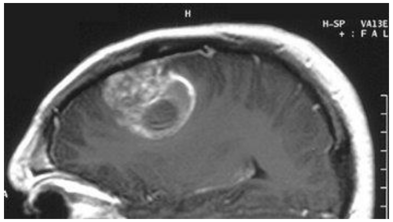
Coordinator: Rachel Delorme

- Offer PRAE: **development and validation of new VHEE technique, Mini Beam and FLASH operation modes, Platform for Radiobiology studies including potentially in vivo studies, Internships and Training**
- Lecture **From Physics to Cancer treatment: current status and advances in Radiation Therapy by Manjit Dosanjh (CERN)**
- Radiobiology session: October 9, 9h-12h.

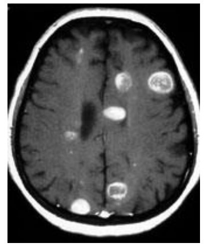
Platform for Research and Applications with Electrons

- Limits of conventional radiotherapy

Resistant, voluminous and diffuse cancers (glioblastomes)



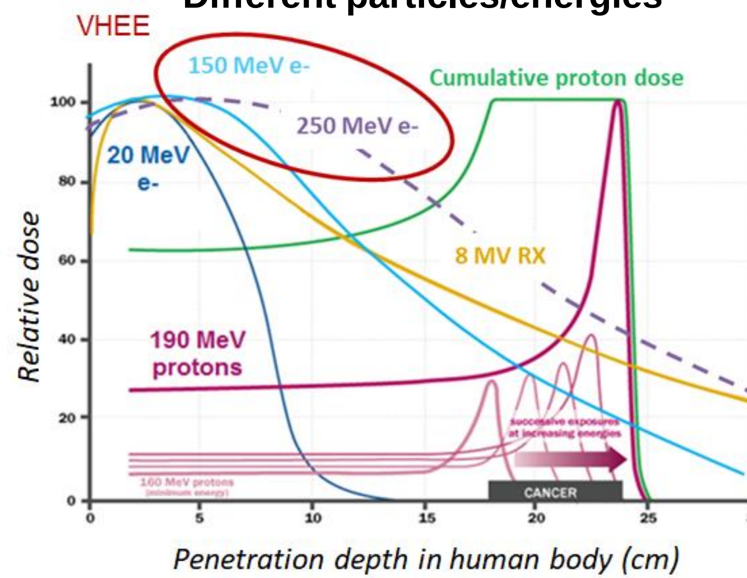
Non-localized tumors (multi-métastases)



- Precision of tumor limits, organ movements, patient repositioning errors
- Toxicity to healthy tissues limits the dose

- Induce more effective tumor irradiation: **hadrontherapy**, **combined therapy** with nanoparticles/chemical agents

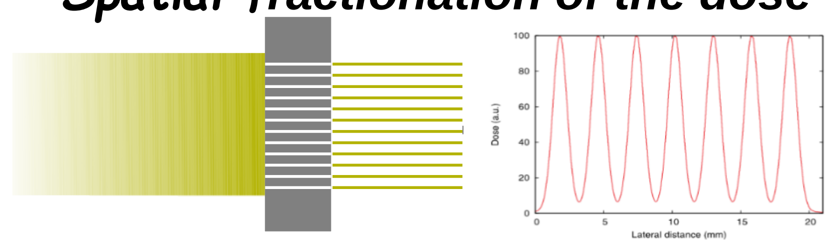
Different particles/energies



- Preserve healthy tissues via dose delivery mode: **MicroBeams** and **FLASH**

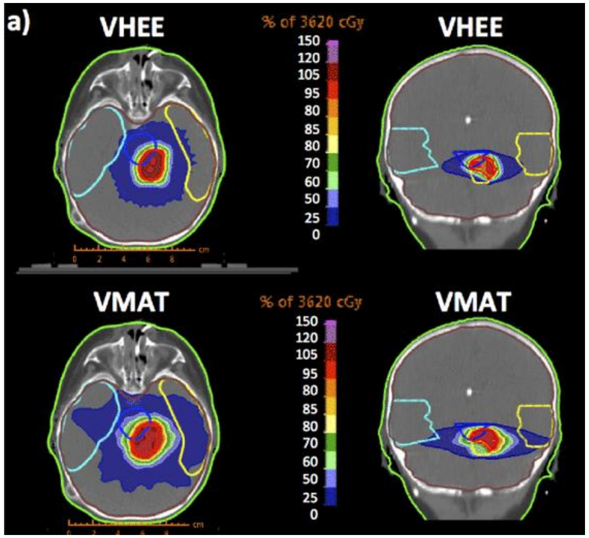
***FLASH therapy**, very high dose rate*
> 40 Gy/s (conventional 0,03 Gy/s)

Spatial fractionation of the dose

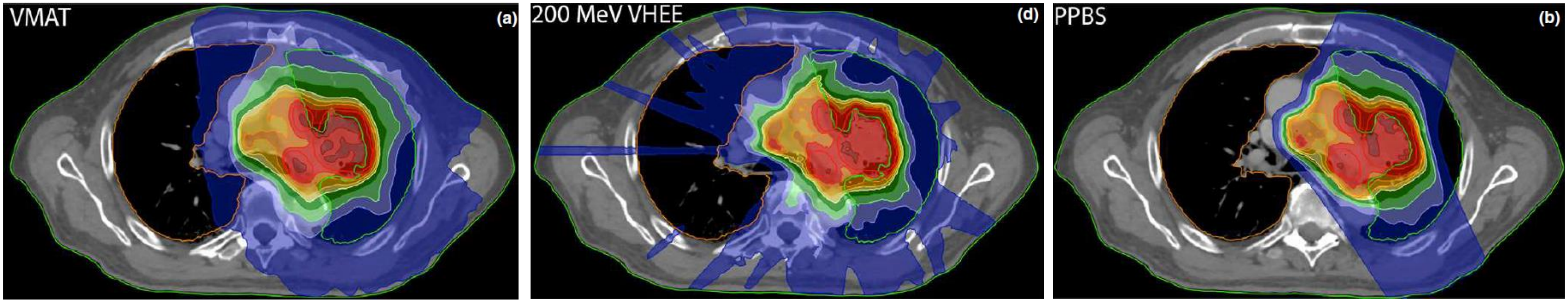


Platform for Research and Applications with Electrons
PRAE

- **VHEE beams vs. MV photons**
- **Dose profile:** deep-seated tumors with flatter profile than photons and reduced penumbrae
- **Magnetic collimation**: pencil beam scanning
- **Heterogeneities:** no electronic disequilibrium at interfaces
- **Clinical case:** compared to VMAT (gold std in photon radiotherapy) better protection of OAR (prostate, pediatric, Lung, brain, H&N…)
- Potentially **cost-effective** approach



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

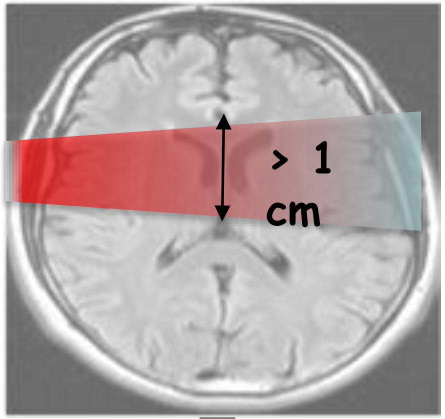


Lung tumor: **X-ray, VHEE, protons** **Schuler, 2017 (Stanford)**

NARA: Spatial fractionation of the dose

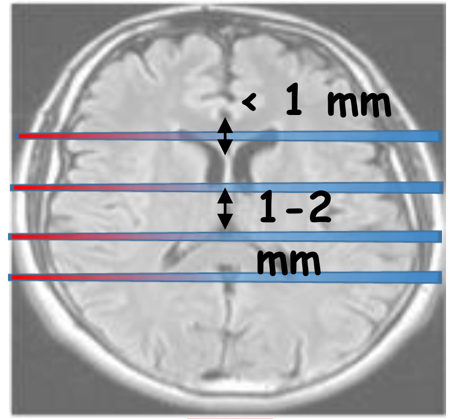
Standard radiotherapy

Large field sizes
(> 1 cm²)
+
Homogeneous dose



Lethal dose > *20 Gy*

Fractionated radiotherapy: *x-rays mini-beams*



Small-size beams spaced by the zones of low dose
+
Heterogeneous dose

100 Gy/session

Prezado et al., 2015

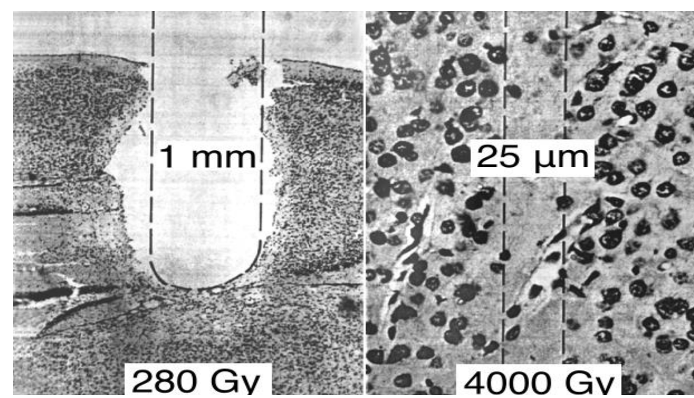
- ❑ Possible dose increase → better tumor control
  Biological mechanisms still poorly known

- ❑ **«Protective» effect of healthy tissues** reproduced with **proton mini-beams** + tumor control increased

Prezado et al., 2017

Radiobiological effect of spatial fractionation :

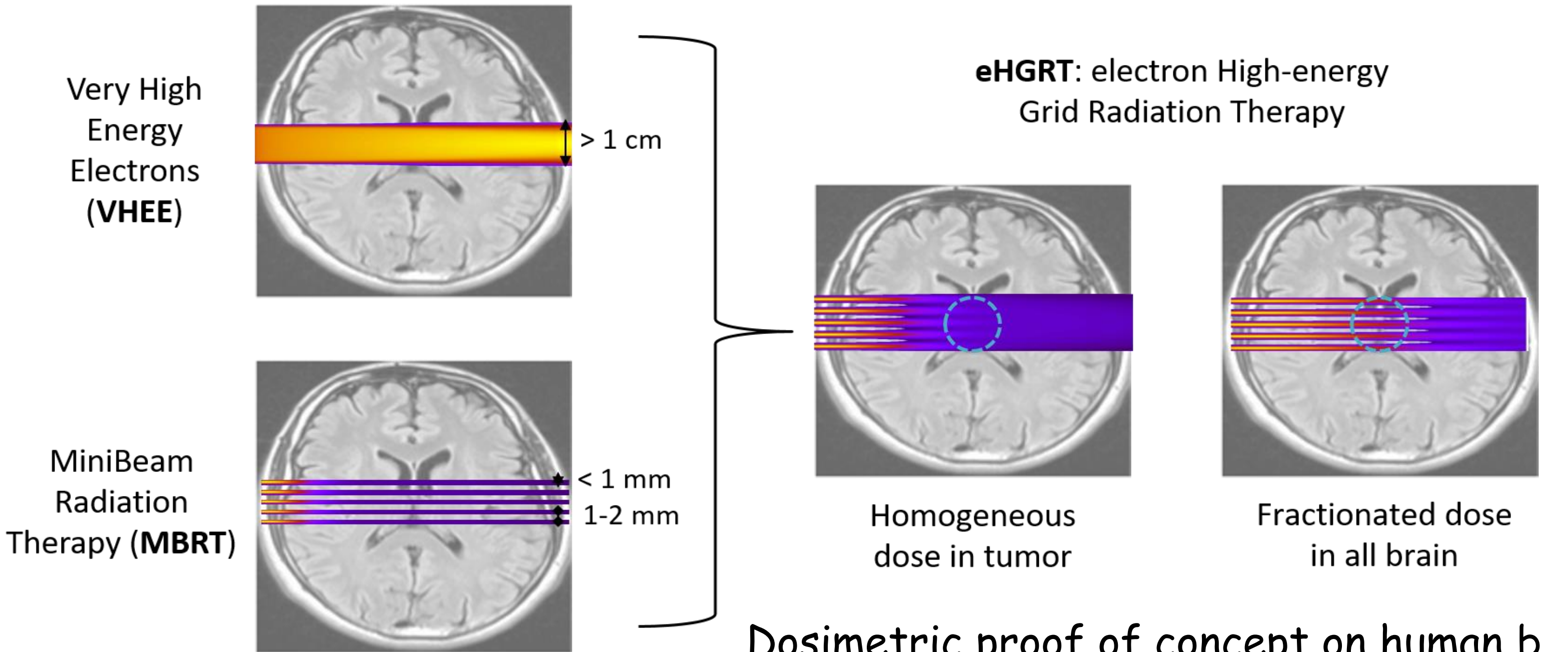
- ❑ **Cell repair and repopulation** in valley regions
- ❑ Differential tissue effect between vascularization «immature» and «mature» ***Bouchet et al.***



Zeman et al., Science (1959)

VHEE grid-therapy: implementation in PRAE

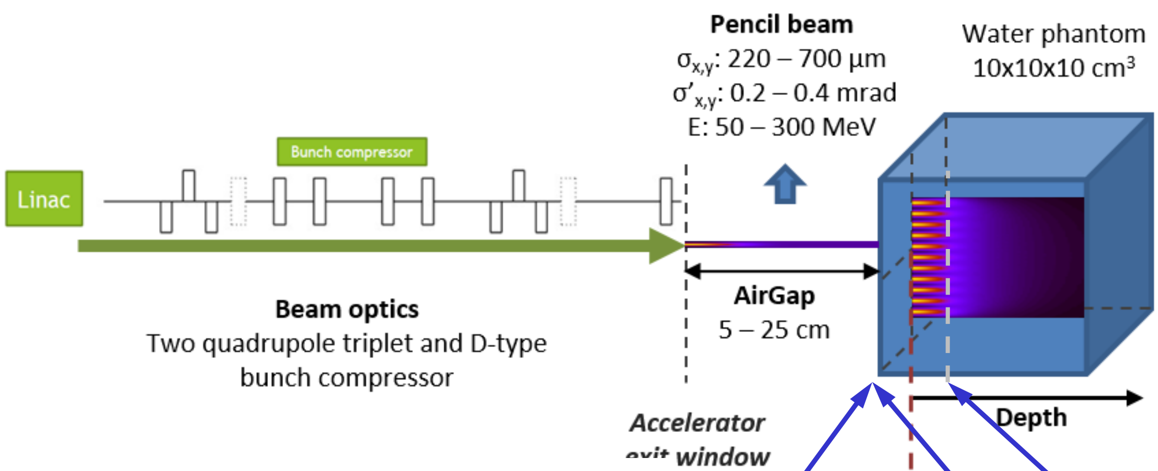
- **Objective:** combine advantages of VHEE beams with spatial fractionation
- **Grid therapy with beams <1 mm**



Dosimetric proof of concept on human brain
Martinez-Rovira & Prezado 2015

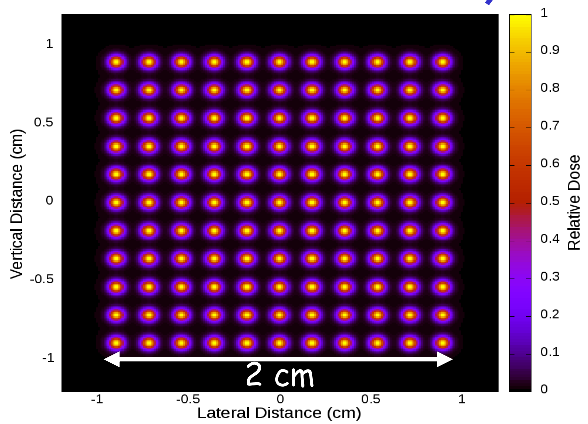
- **PRAE**: numerical and experimental dosimetric **validation up to the *in vivo* proof of concept** on rats

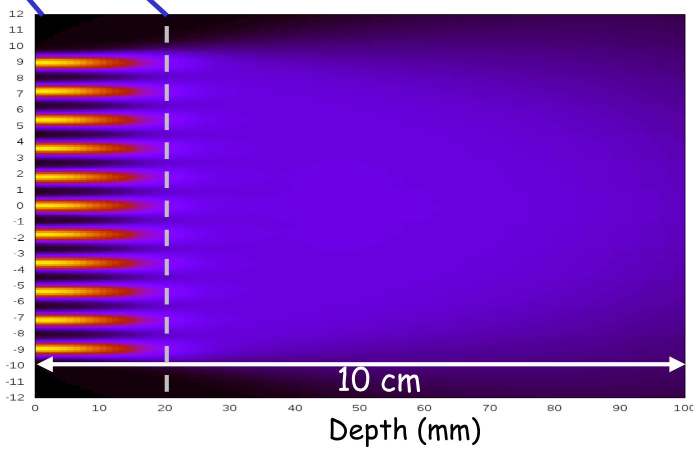
❑ Beam-optics calculations for preclinical experiments



dose fractionation at entrance

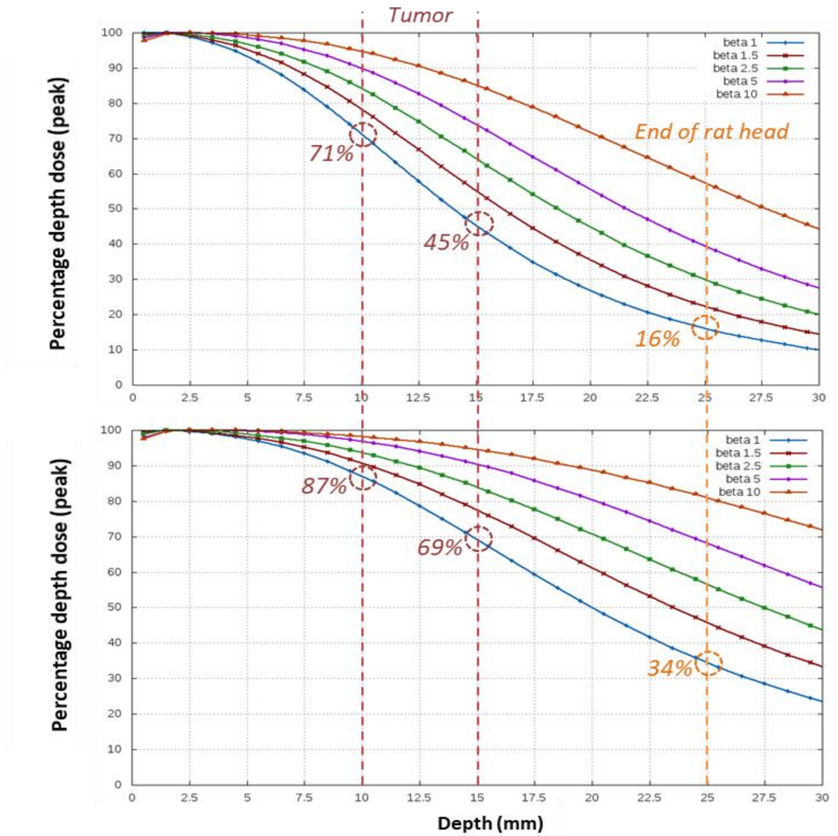
dose homogeneisation with depth





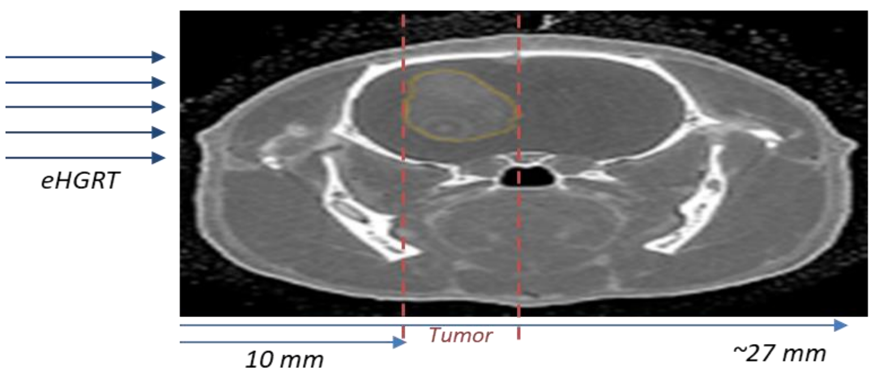
Dose calculation of VHEE grid-therapy in a rat-head CT image: 140 MeV, σ=250μm

ESTRO 2018: Delorme R. et al. EP-2198
IPAC 2018: A. Faus-Golfe et al. MOPML051

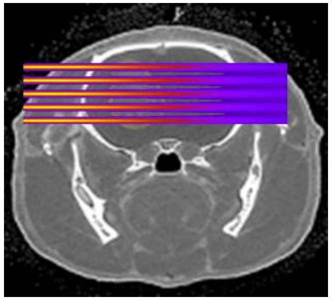


70 MeV

140 MeV



Example of rat head with a brain tumor
-
Typical depth of interest

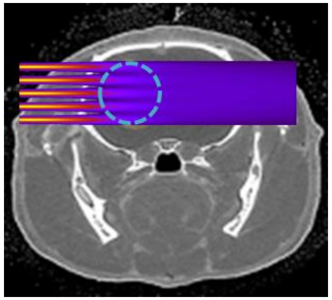


E=140 MeV, σ~250 μm *(SFR)*:

- ❑ Submillimetric over all depth
- ❑ Dose sufficiently large to control a tumor

E=70 MeV, σ~350 μm (partial SFR)

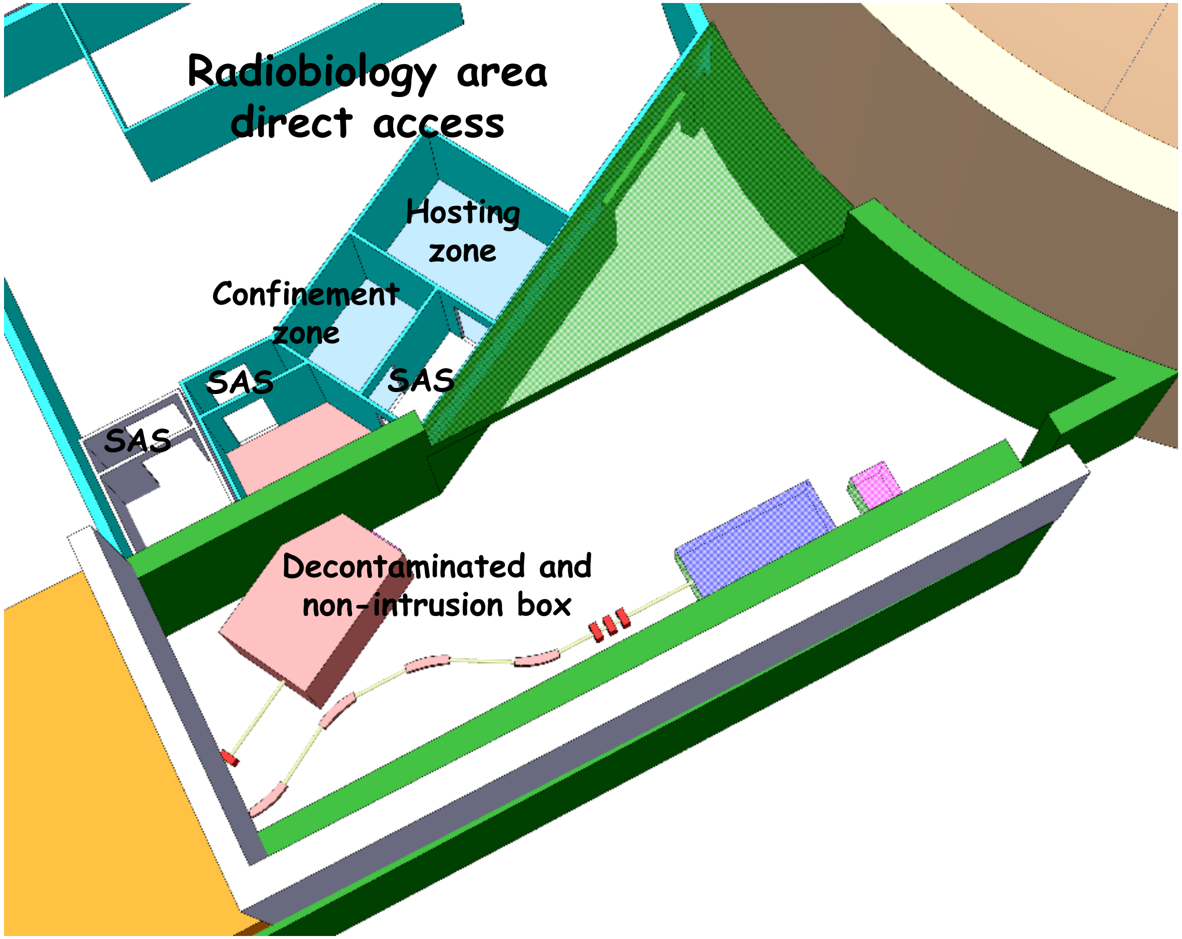
- ❑ Submillimetric < 10 mm
- ❑ Dose homogeneous in tumor



- **PRAE radiobiology line**
  - **Experimental dosimetry for very small field sizes**: with radiochromic films and microdiamond detector
  - Monte Carlo dose calculation: beam characteristics for eHGRT, validation of experimental dosimetry, dose calculation for radiobiology studies
  - **Radiobiology studies on cells and small animals**: confirmation of the hypothesis of high normal tissue resistance
  - **Relative Biological Efficiency (RBE) of VHEE** with respect to photons
  - Studies of the **FLASH effect**

- **Open for new ideas and collaborations**

- **Preparation area for biological experiments**
- **Decontaminated and non-intrusion area** to answer the ethic constraints for animal experimentation
- Possibility to extend dedicated Radiobiology area



Instrumentation

Coordinator: Bernard Genolini

- Offer PRAE: **Versatile platform for detector R&D and tests, Calibrated beam with adjusted and known kinematics and number of electrons per sample, Internships and Training**

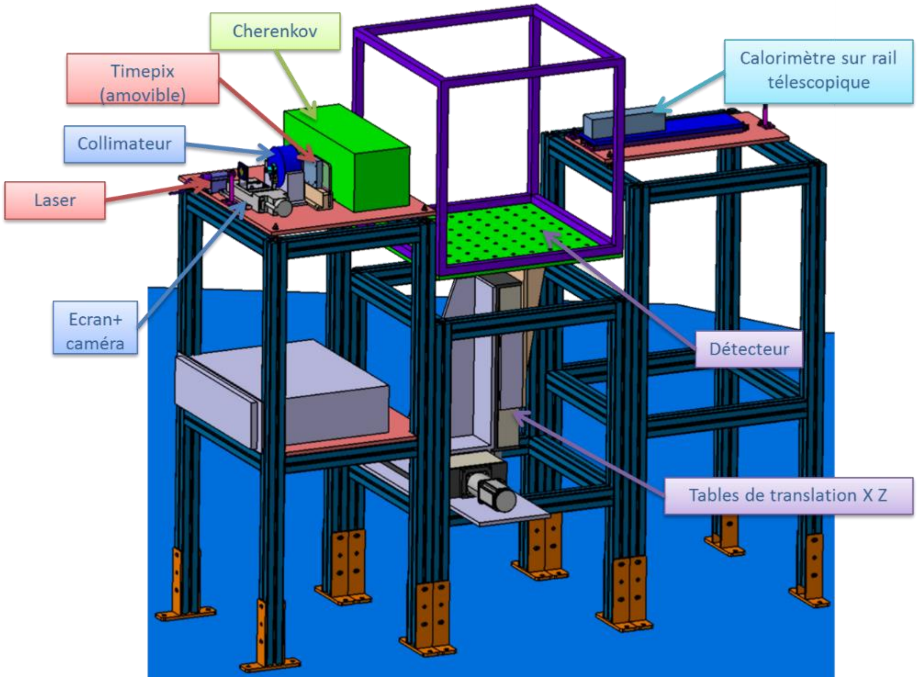
- Instrumentation session: October 10, 9h-12h.

- **Local 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

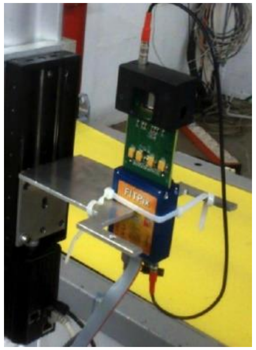
Measure the time, charge and imaging performance of particle detectors

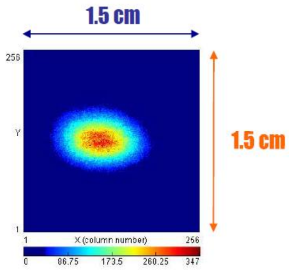
→ *Calibration for charge, trigger, tracking detectors*

Instrumentation platform at PRAE



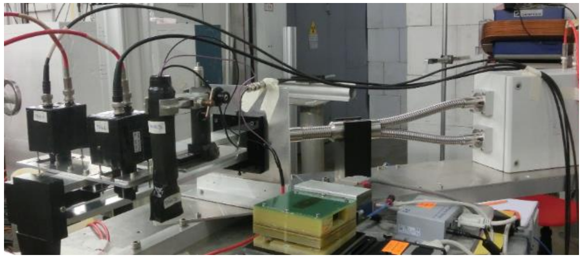
Timepix detector for precision spot measurement

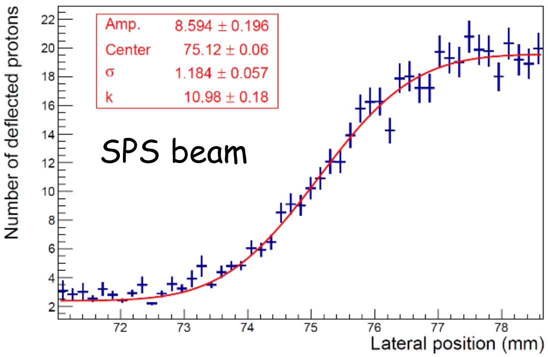




Cherenkov quartz counter for intensity monitoring

Example of Cherenkov counters developed at LAL

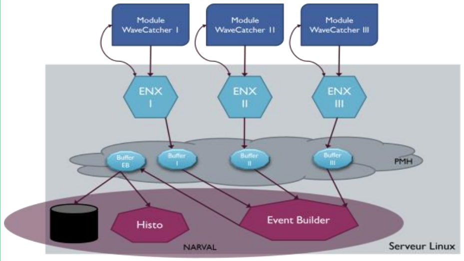




DAQ + slow control

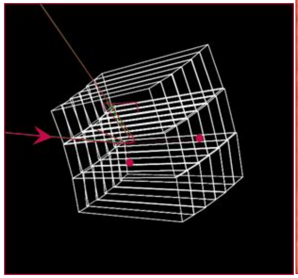
WaveCatcher developed at LAL

NARVAL developed at CSNSM



Calorimeter for energy monitoring

BGO scintillator crystals in compact matrix geometry

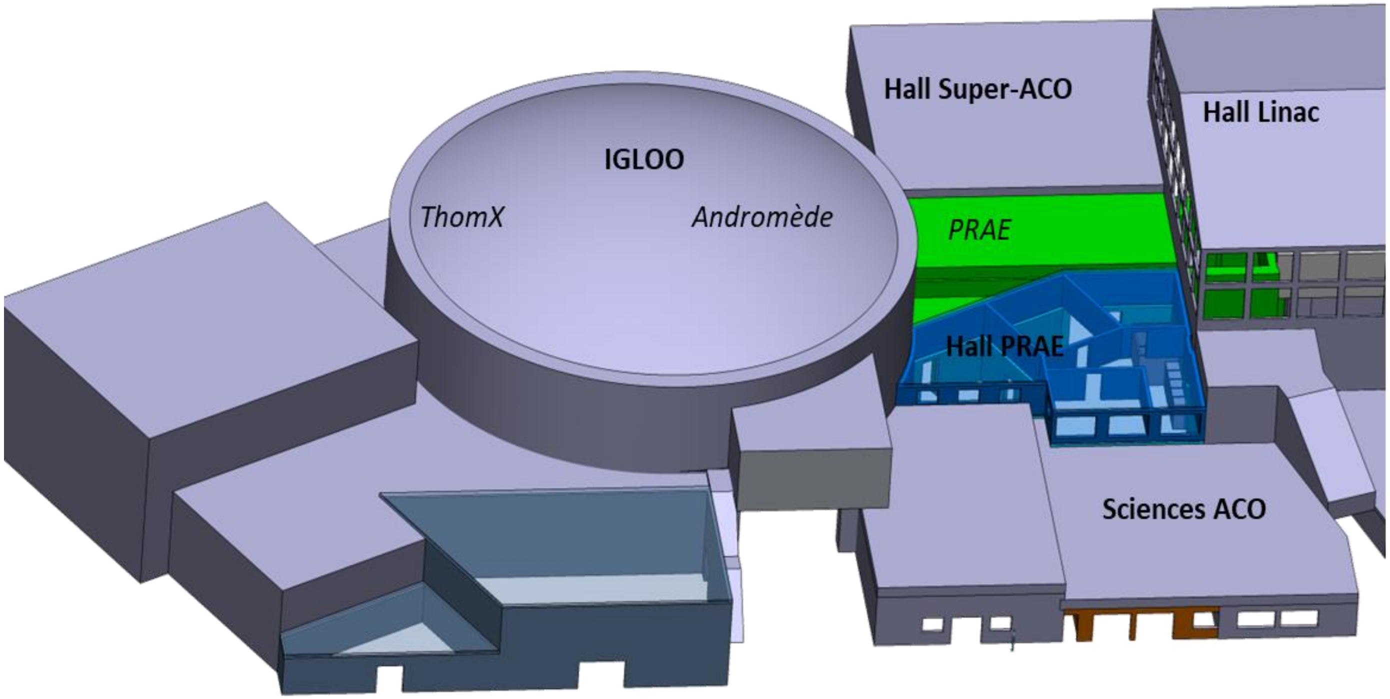


Example of a calorimeter realized at IPN

PRAE site and infrastructure

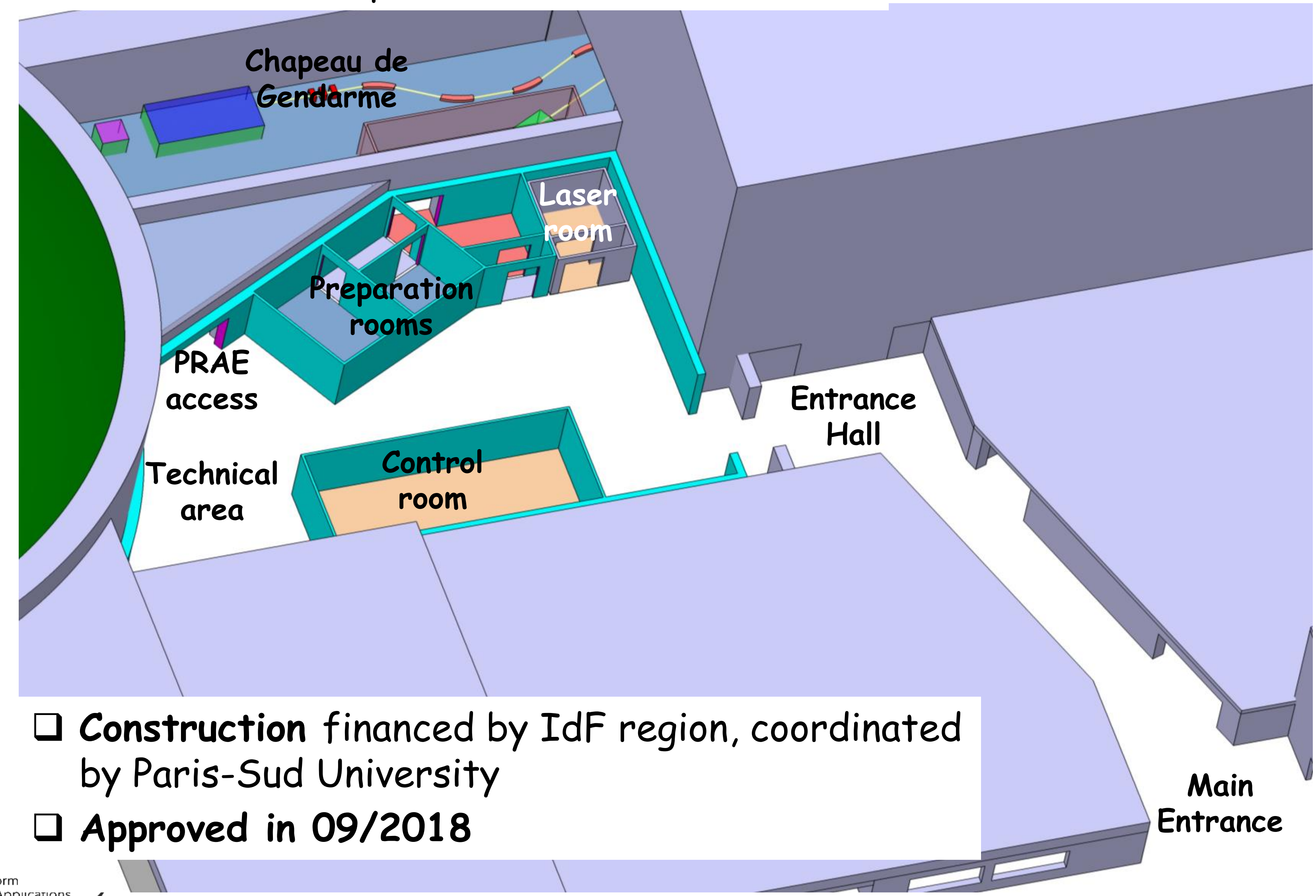
Coordinator: Patricia Duchesne

- PRAE experimental hall - existing structure, locked and radio-protected site



PRAE site layout

- Ground floor of new building
- Direct access to radioprotected area



- **Construction** financed by IdF region, coordinated by Paris-Sud University
- **Approved in 09/2018**

- PRAE is a project for science, R&D and applications based on **complementary expertise of major Orsay laboratories**.
- Construction of the **multi-disciplinary PRAE site – Subatomic physics, Radiobiology, Instrumentation R&D and Accelerator** – is centered around the **new high-performance electron accelerator**.
- Operation is expected to start in 2021.
- PRAE offers a variety of **opportunities for research, applications and training.**
- PRAE is open for new groups, new ideas and new proposals.

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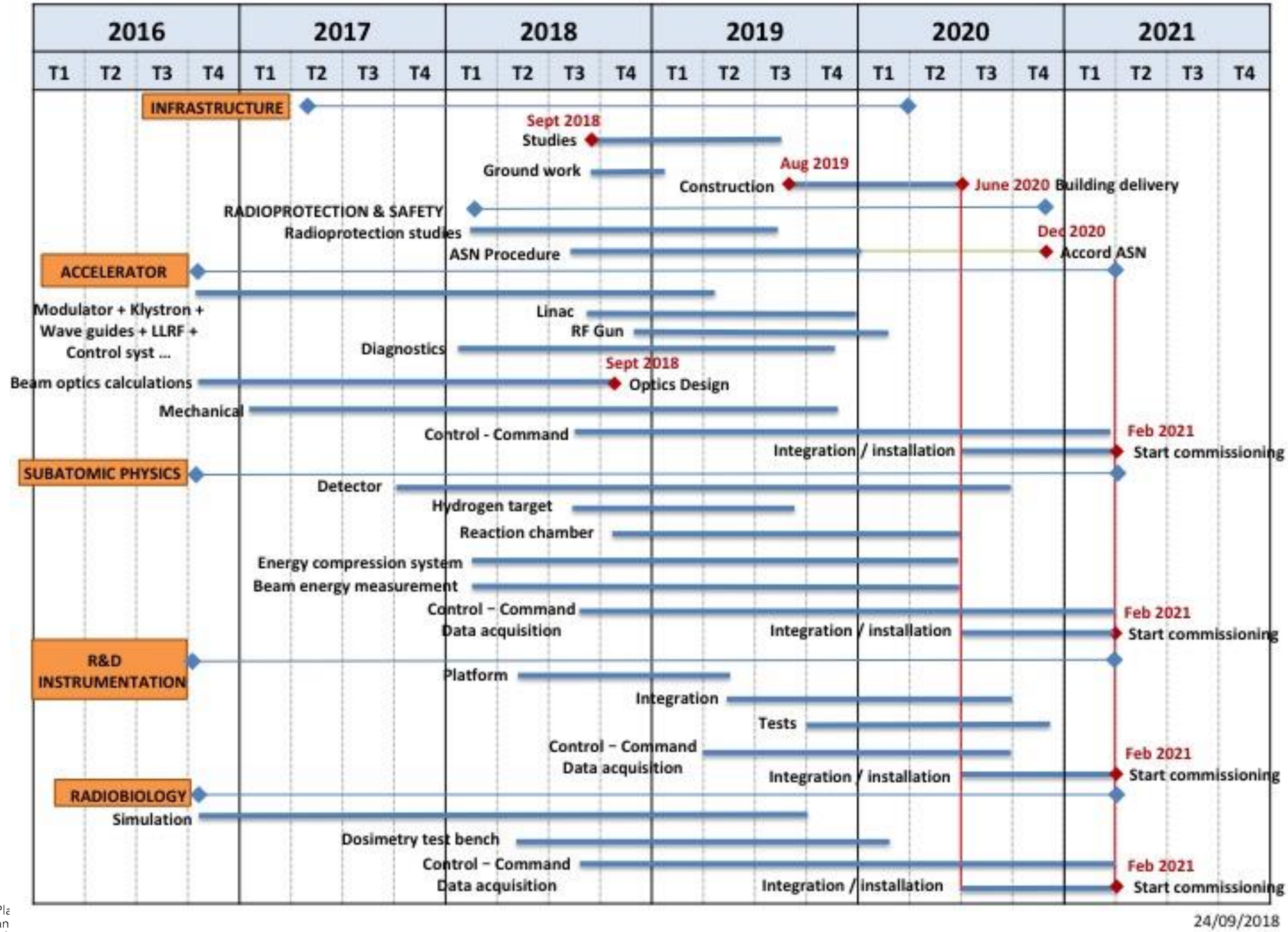
- **New PRAE Project Manager: Cynthia Vallerand.**

Backup

Planning


2016
2017
2018
2019
2020
2021
T1 T2 T3 T4
INFRASTRUCTURE
Sept 2018
Studies
Ground work
Aug 2019
Construction
June 2020 Building delivery
RADIOPROTECTION & SAFETY
Radioprotection studies
Dec 2020
ASN Procedure
Accord ASN
ACCELERATOR
Modulator + Klystron +
Wave guides + LLRF +
Control syst ...
Linac
RF Gun
Diagnostics
Sept 2018
Beam optics calculations
Optics Design
Mechanical
Control - Command
Feb 2021
Integration / installation
Start commissioning
SUBATOMIC PHYSICS
Detector
Hydrogen target
Reaction chamber
Energy compression system
Beam energy measurement
Control – Command
Data acquisition
Feb 2021
Integration / installation
Start commissioning
R&D INSTRUMENTATION
Platform
Integration
Tests
Control – Command
Data acquisition
Feb 2021
Integration / installation
Start commissioning
RADIOBIOLOGY
Simulation
Dosimetry test bench
Control – Command
Data acquisition
Feb 2021
Integration / installation
Start commissioning
24/09/2018

European facilities, table

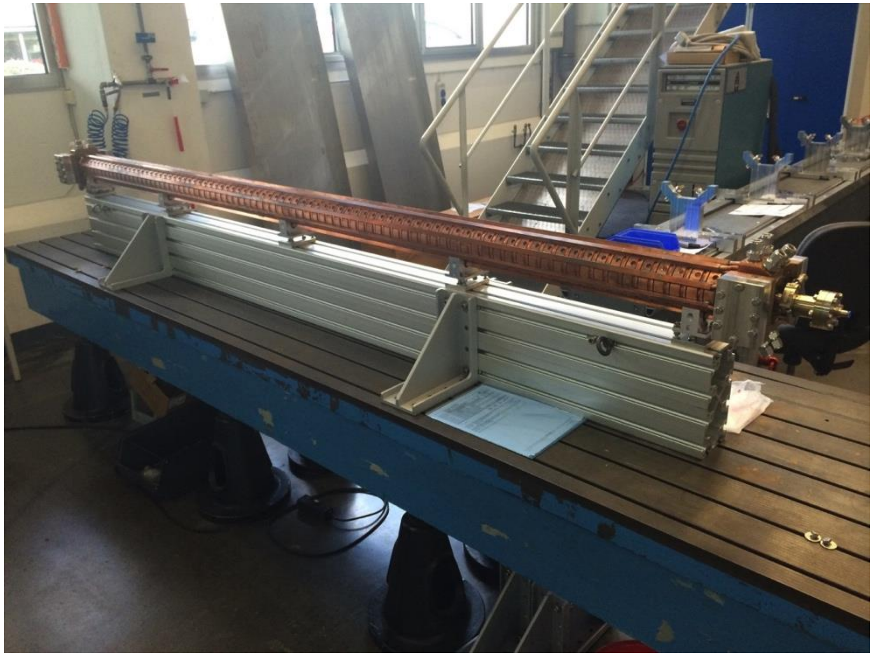
(this worksheet is now protected, please contact Erik Adli if you have modifications/corrections.)	EUROPE (only primary beams)									
Name	CALIFES	CLARA	FlashForward	Sinbad	PITZ	SPARC_LAB	Max IV injector	PRAE	RADEF (clinac)	FLUTE
Country	Switzerland	UK	Germany	Germany	Germany	Italy	Sweden	France	Finland	Germany
Laboratory	CERN	Daresbury	DESY, Hamburg	DESY, Hamburg	DESY, Zeuthen	INFN, Frascati	Max IV	Orsay, France	Jyväskylä	KIT
Type of facility	TBD	Test facility for UKFEL R&D	DESY tests of PWFA	Adv. accel. research	Photo-inj test facility	Adv. accel. research	Part of Max IV. Ideas (but no funding) to create a 3 GeV ebeam test facility	Multi-disiplinary	Medical linac (?)	THz tests
Online when?	Online	Jan 2017 (50 MeV)	mid-2017	2018 ?	Online	Online	Linac under final commissioning. Parameters as expected when fully commissioned.	2020 ?	online	online (?)
Energy	130-200 MeV (60 with upgrade)	50 MeV (Jan 2017) 250 MeV (Sept 2019)	1.25 GeV	100 MeV	25 MeV	150 MeV	3 GeV	65 MeV	<= 20 MeV	41 MeV
Energy spread	< 1 MeV FWHM (< 0.2 % rms)	25 to 100 keV rms	0.10%	< 0.3% (low charge, peak	<0.5%	0,1%	<0.05% + chirp	0.2 % rms		
RF Frequency	3 GHz	3 GHz		3 GHz	1.3 GHz	2.856 GHz	3 GHz	3 GHz		
Rep. rate	1 or 5 Hz (25 Hz with upgrade)	100Hz at 250MeV, 400Hz at 100MeV	10 Hz	10 - 50 Hz	10 Hz	10 Hz	10 (100) Hz	50 Hz		10
Time structure	1.5 GHz, or single bunch	single bunch	single or double bunch	single bunch	up to 600 bunches at 1 MHz rep rate	single bunch or up to 4 bunches at 1 THz rep rate		single bunch		single bunch (?)
Bunch length	4 ps FWHM (~ 500 um rms)	35 fs to 1.9ps FWHM	10-500fs	sub-fs - 2 fs (low charge)	Flat top, 2ps rise/fall time; 22ps FWHM	30 fs - 5 ps	10-500 fs	10 ps		1 - 300 fs
Charge per bunch	10 pC to 0.5 nC (for < 30 bunches)	25 to 250pC	250 pC	0.5 pC - 20 pC for fs bunc 1 nC possible	20 pC to 4 nC	0.1-0.8 nC	20-200 pC	sub pC - 2 nC		1 - 3000 pC
Trans. emittance Normalized	3 um for 0.05 nC bunches, 20 um for 0.4 nC	0.5 to 1.0um	2 um	< 0.5 um	0.6 um for 1 nC	1 um	< 1um	3 - 10 um		

Platform for Research and Applications with Electrons

TW S-Band structures from RI

Parameter	Value
Length	3.5m
Number of Couplers + Cells	1+96+1
Type	Constant gradient
Phase Advance	$2\pi/3$
Frequency	2998.55 @ 30° C
Pulse Width	3µs
Repetition Rate	50Hz
Max. input Power	40 MW
Max. average power	5 kW

- SLAC-type structures
- Constant gradient
- Race track coupler for quadrupole compensation
- BIG Splitter for dipole compensation
- 2 RF loads



- **Expected delivery in 10/2019**

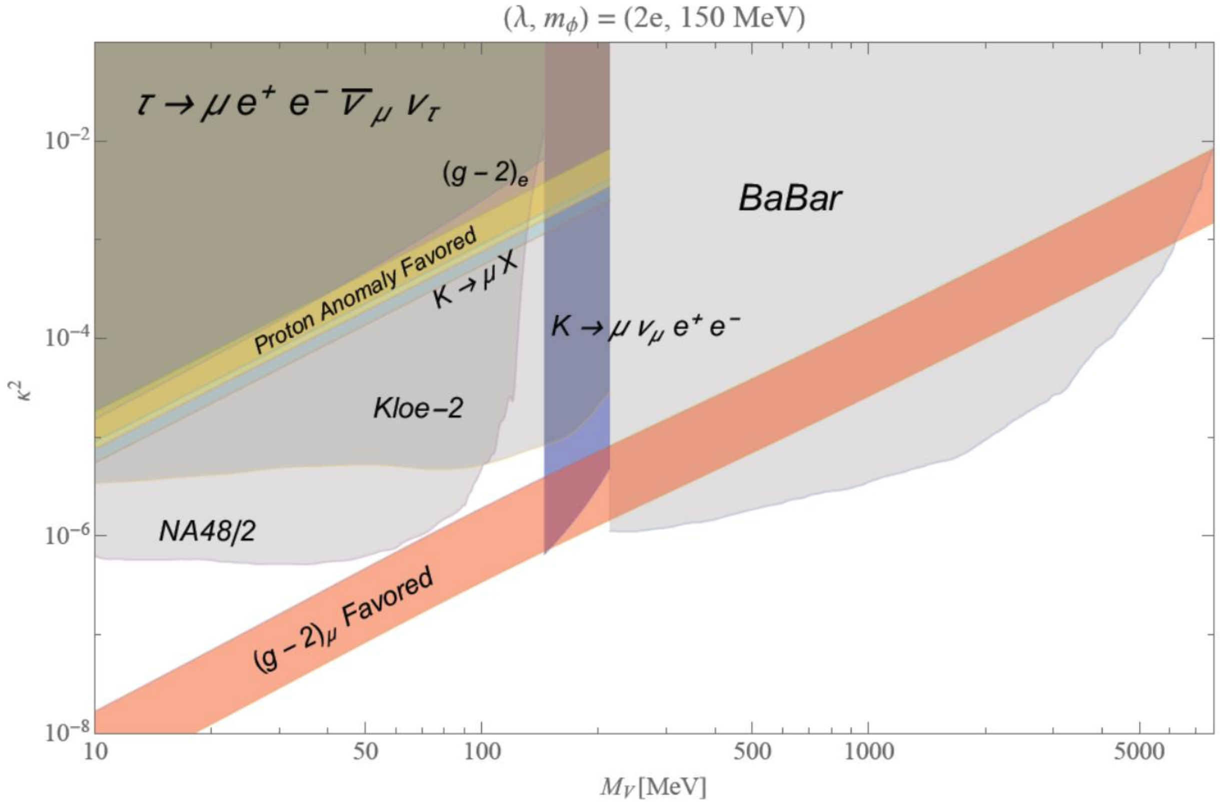
Klystron specifications	Value
Frequency Functioning mode	Pulsed
Repetition Rate	50 Hz
Beam Pulse Width (mid-height)	≥ 6,5 µS
RF Pulse Width (flat top)	≥ 4,5 µS
Peak RF output power	≥ 45 MW
Nominal beam voltage	≥ 10 kW
Nominal beam current	340 A
Micro-perveance	2
Efficiency (@ saturated RF output power)	≥ 43%
Gain (@ saturated RF output power)	≥ 47
Bandwidth -1dB (@ saturated RF output power)	≥ 8 MHz
RF input power	≤ 500 W
Nominal load VSWR	≤ 1.1:1
Sustainable load VSWR	≥ 1.35:1

CPI
Communications & Power Industries
microwave power products division

- Expected delivery in 10/2019

Model of DM (F. C. Correia, S. Fajfer, arXiv:1609.0860, Batell et al., arXiv:1103.0721):

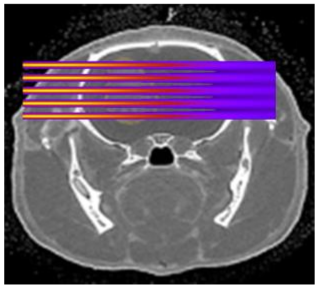
- V is the gauge boson, neutral under the SM gauge group and charged under $U(1)_d$
- κ is a mixing angle between dark boson and photon



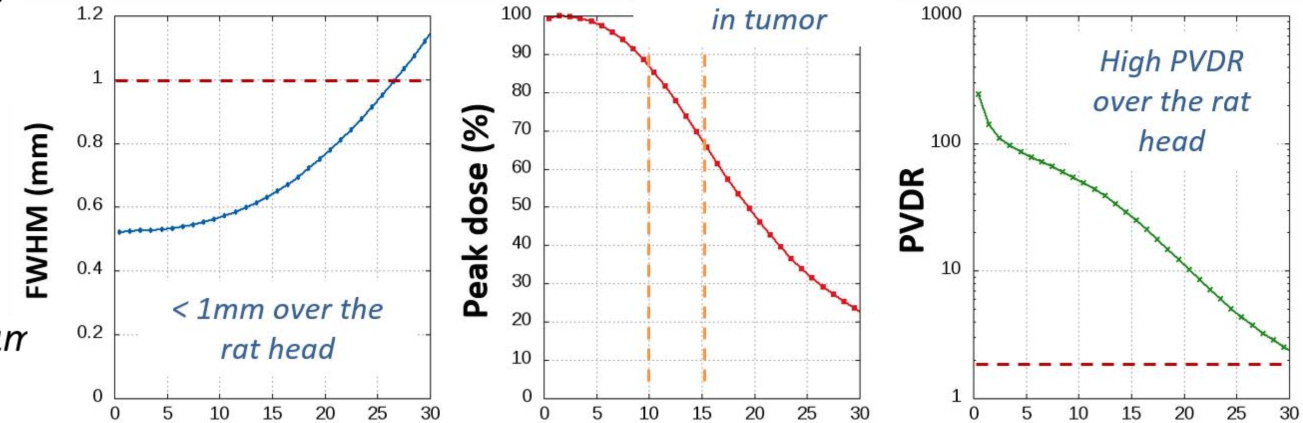
- Colour areas are excluded (for proton charge radius and $(g\text{-}2)_\mu$ yellow and red are favored)!

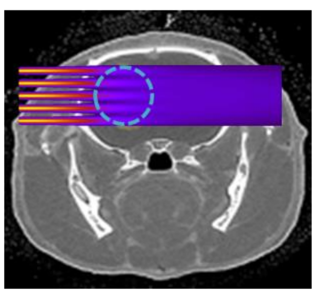
VHEE grid-therapy: Dosimetry evaluation

First dosimetry optimization: electron energy, beam size, beam divergence , air gap

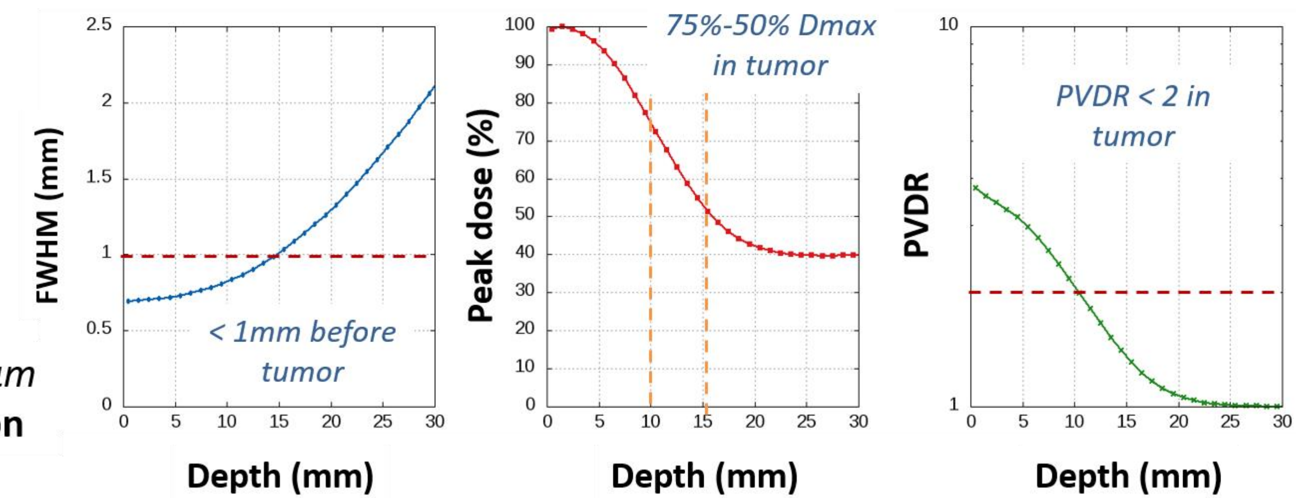


140MeV, σ 220µm, ctc 1800µm
Healthy tissue sparing optimization





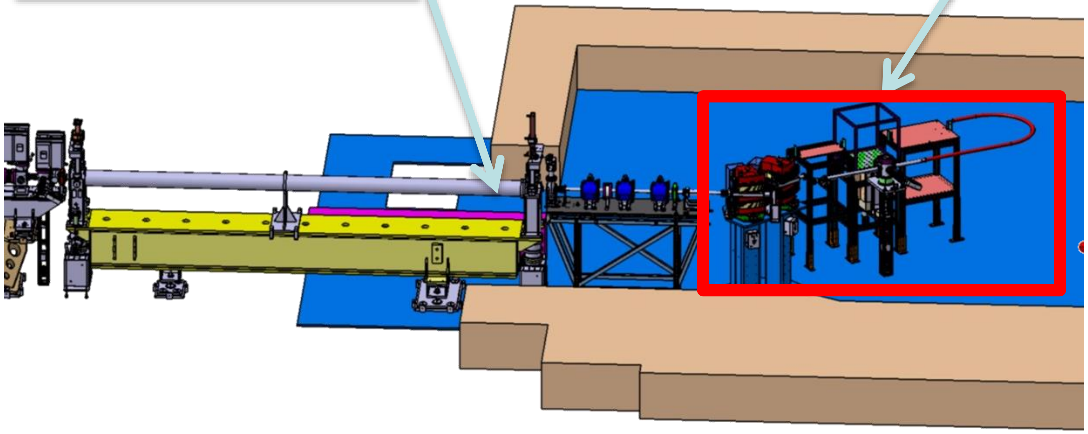
70MeV, σ 220µm, ctc 1200µm
Tumor control optimization

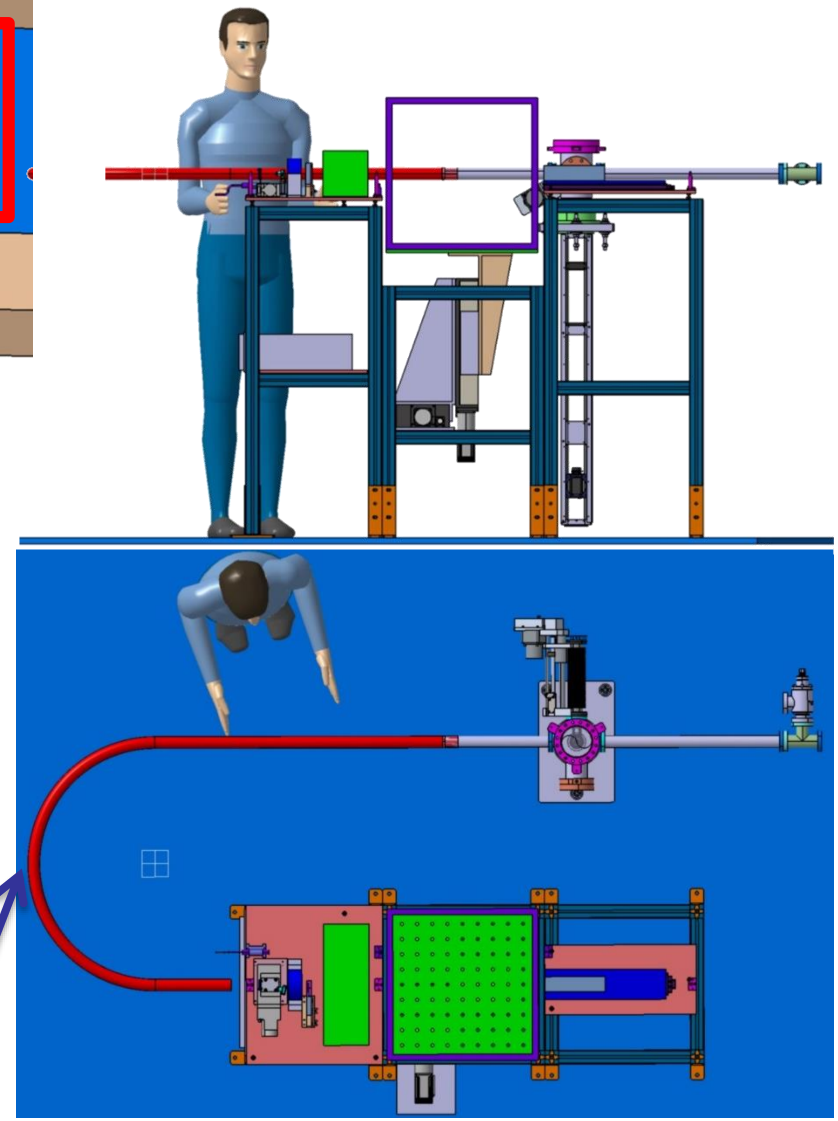


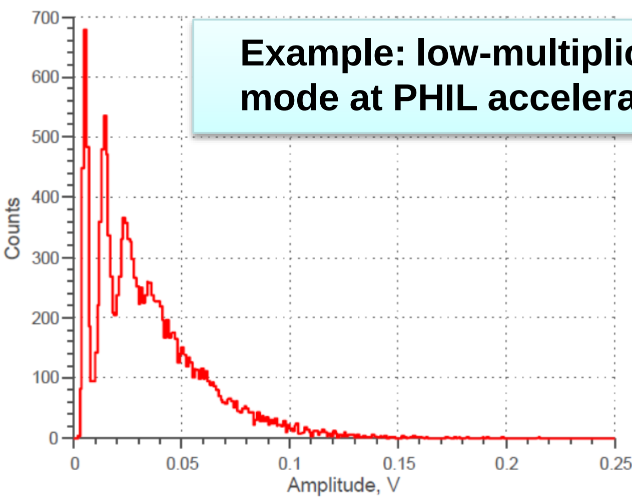
Delorme R. et al. EP-2198. Radiother Oncol. 2018;127:S1214-S1215.

Ligne accélératrice

Plateforme







Example: low-multiplicity mode at PHIL accelerator

SPECTROMETER

Platform for Research and Applications with Electrons