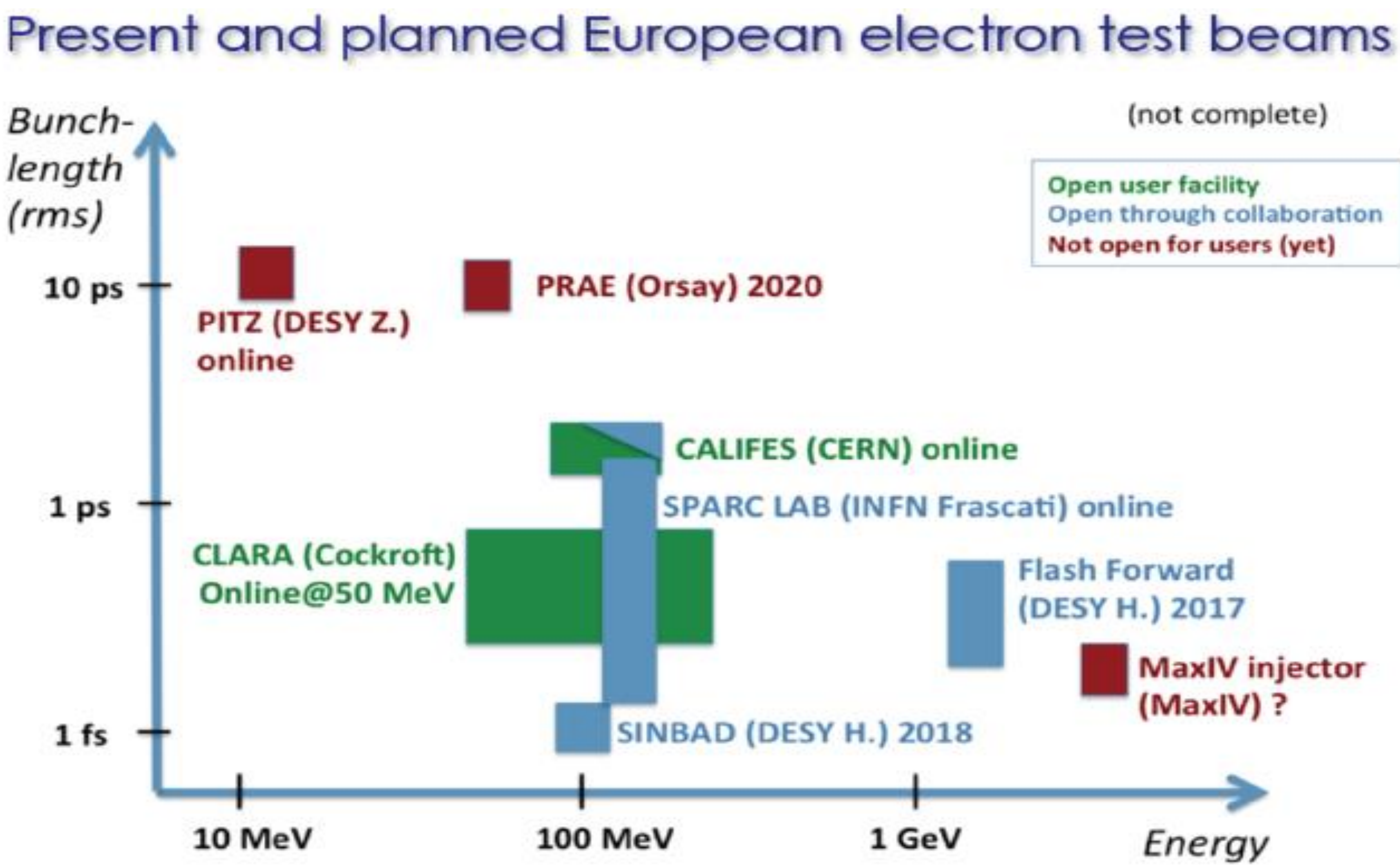
Task 3.4: Medium energy electron beams: new technology development

A. Faus-Golfe
on behalf of the LAL team

Motivation:

From lowest to highest energies, electron beams represent exploration and measurement tools of high quality and unparalleled wealth. If the number and quality of research tools at both ends of the energy scale are encouraging, it should be noted the **poverty** of the **accelerator park** in the **range of tens to hundreds of MeV**.



Task objectives

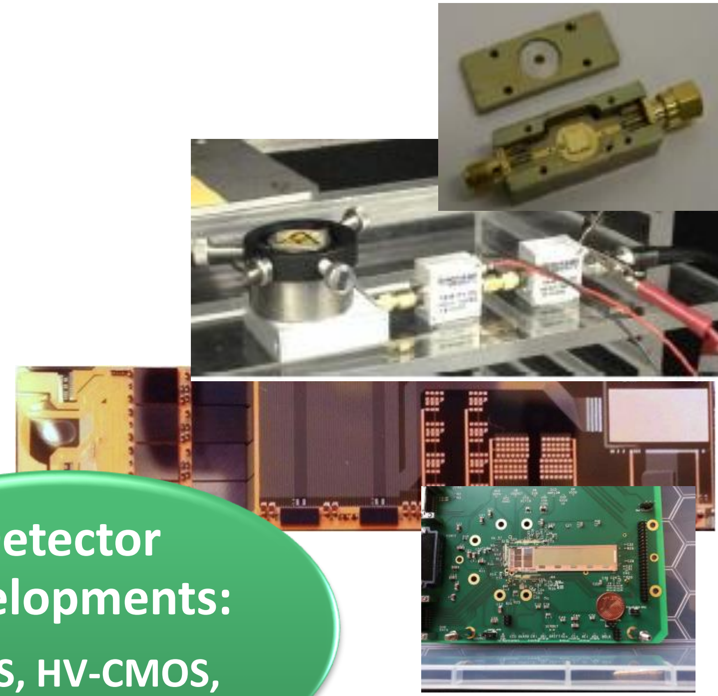
Applications of electron beams and construction of high performance electron linear up to 140 MeV

Biomedical:

New radiotherapy approaches: mini-beams, flash…

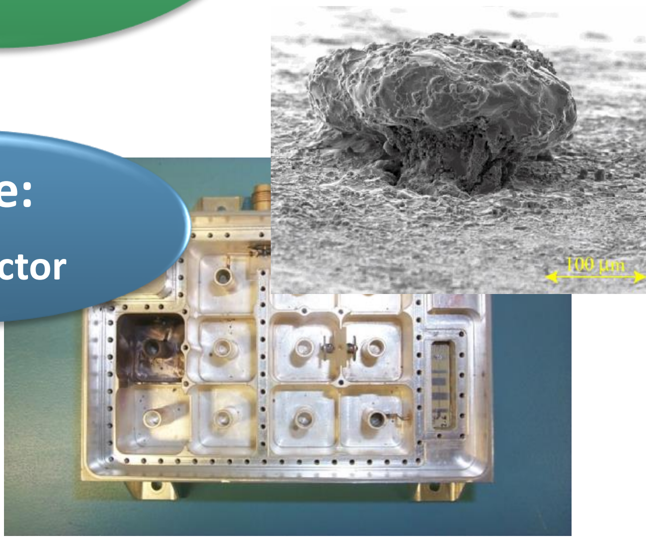
Detector Developments:

MAPS, HV-CMOS, DEPFETs, Diamonds



Space:

Multipactor



Others:

Subatomic physics, laser, beam instrumentation, laser plasma lens, THz radiation…

Work plan:

- Organization of **dedicated workshops**:
  - There is already one being organized in medical applications https://www.cockcroft.ac.uk/events/VHEE17/
  - Special session in the CLIC 2018 workshop dedicated to CLEAR where the applications in: beam instrumentation developments (cavity BPMs, Diamond Cherenkov diffraction beam size monitor, Electro-Optical BPMs, wake field monitors…) , irradiation of material and components, plasma lens acceleration, Tera-Hertz radiation developments, VHEE RT, https://indico.cern.ch/event/656356/overview
  - A general workshop the other possible applications will be organized at Fall 2018 in Orsay (PRAE).
- Make a **survey** about the **accelerators** at this energy **in Europe** and investigate what will be the best technology in order to make more compact (**High-Gradient** warm linac...), efficient and adapted to the different applications. Synergies with others EU projectshttp://www.compactlight.eu

Projet Emblématique

Programme SESAME

PRAE:

Platform for Research and Applications with Electrons

A. Faus-Golfe

on behalf of the PRAE team

Imagerie et Modélisation en Neurobiologie et Cancérologie

Institut de Physique Nucléaire

Laboratoire de l'Accélérateur Linéaire

and support from

Centre de Protonthérapie d'Orsay

The PRAE Project

❑ PRAE
- Multidisciplinary R&D Platform
- Transversal, Complementary expertise

❑ PROJET PHASES
- Phase A (2016-2019) : 70 MeV
- Phase B (from 2020): 140 MeV

Scientific responsible

Sergey Barsuk (LAL)

Technical coordinator

Patricia Duchesne (IPNO)

User's coordinator

Dominique Marchand (IPNO)

❑ 4 AXES DE DEVELOPPEMENT

Accelerator

Angeles Faus-Golfe (LAL)

Nuclear Physics

Eric Voutier (IPNO)

Detectors R&D

Bernard Genolini (IPNO)

Radiobiology

Yolanda Prezado (IMNC)

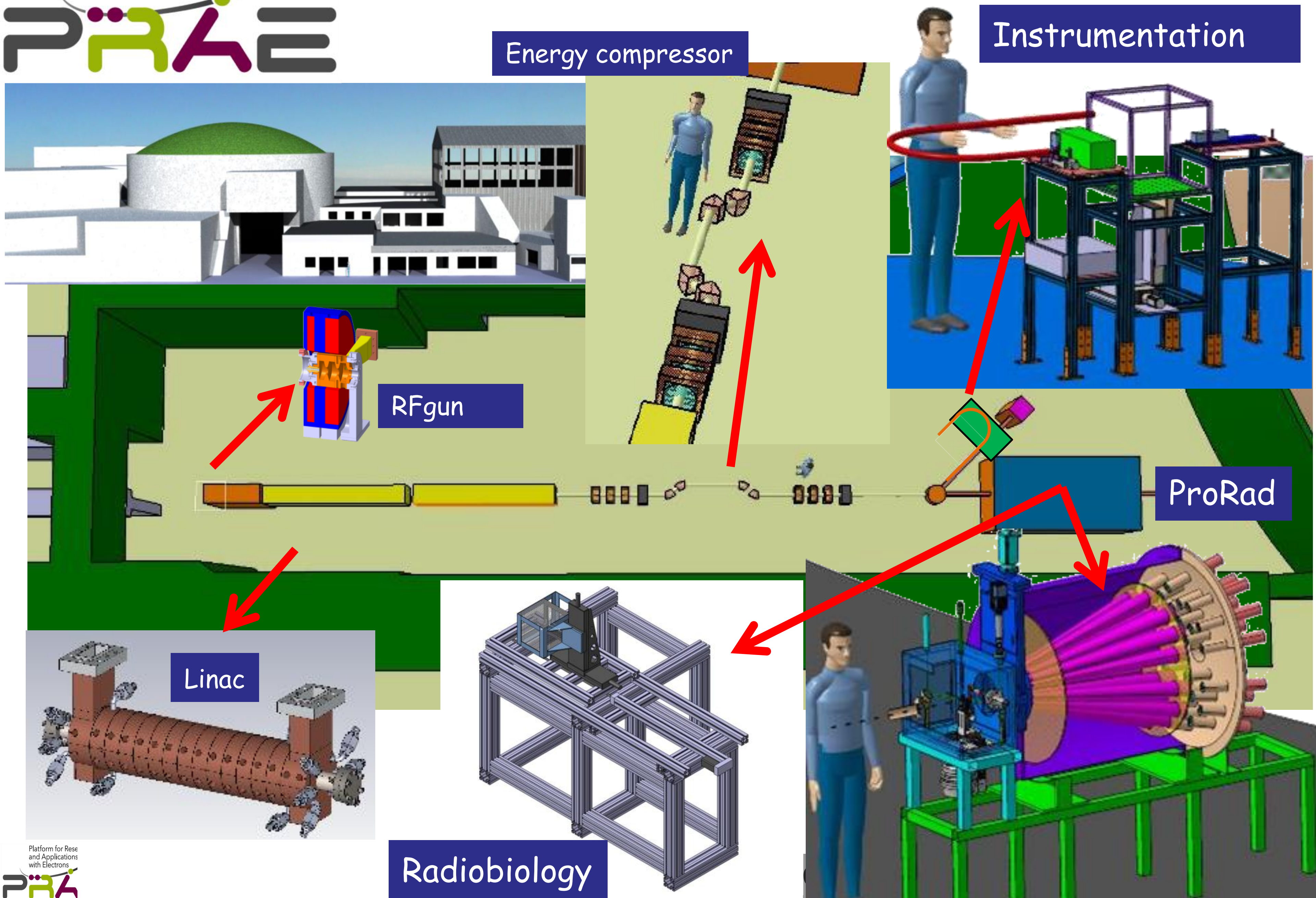
❑ FUNDING

P2IO

îledeFrance

Platform for Research and Applications with Electrons

PRAE in one slide



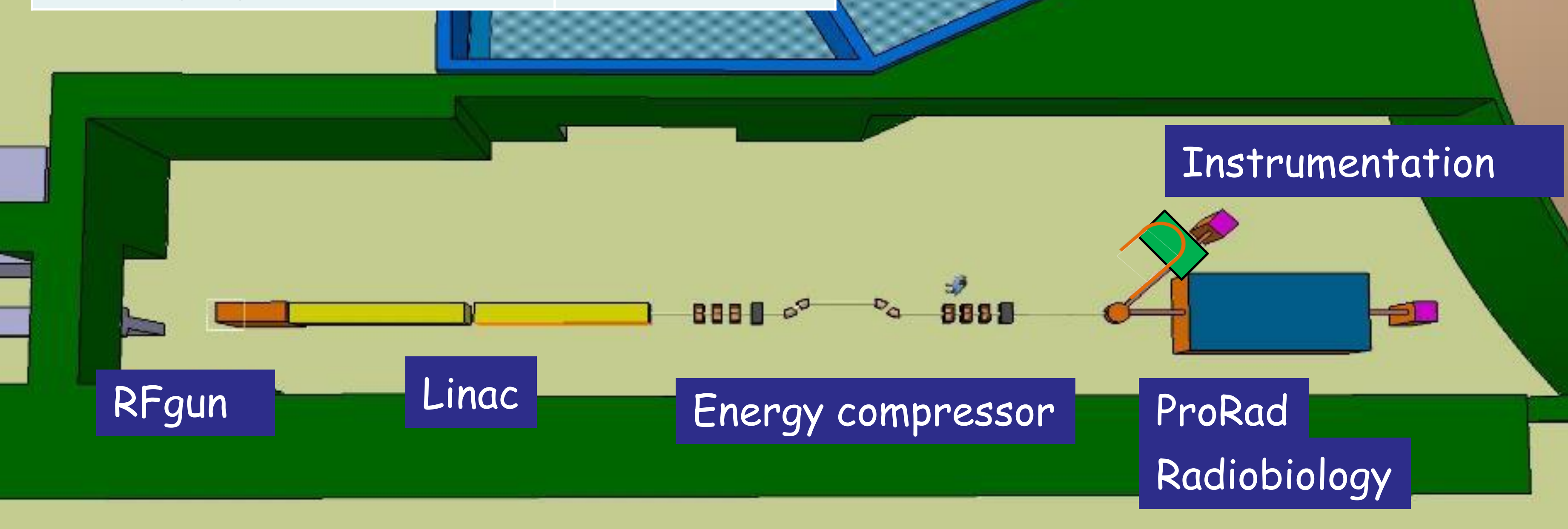
The accelerator construction and related R&D

- *Parameters and Phases*
- *RF gun and High-Gradient Linac*
- *Optics design and simulations*
- *Beam diagnostics*

PRAE Parameters and Phases

Beam parameters	Phase A-B
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

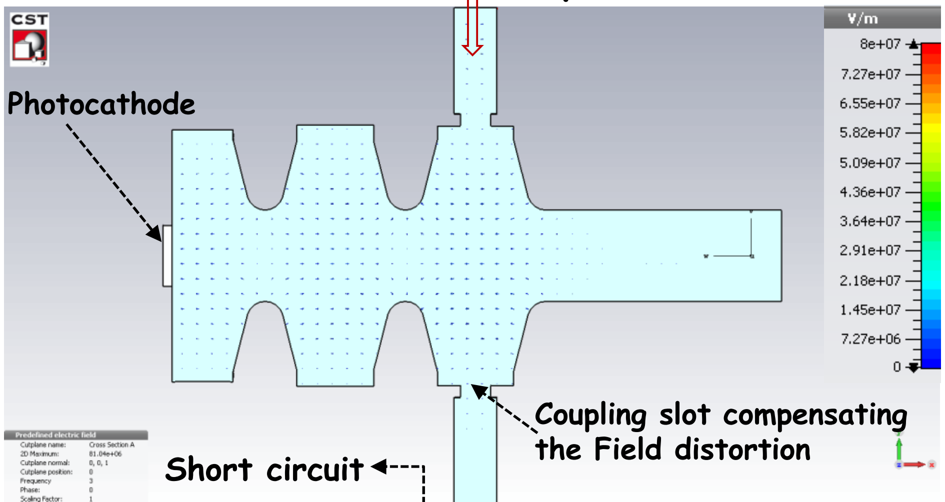
- **Phase A:** RF gun at 50 Hz; 50-70 MeV, two lines:
  - Direct: magnetic chicane for ProRad and radiobiology in mode "Push-Pull"
  - Deviated: for Instrumentation
- **Phase B:**
  - Spectrometer for Instrumentation line
  - Scanning dipole for radiobology
  - Complete set of channels
  - 140 MeV



The RF gun "revisited"

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

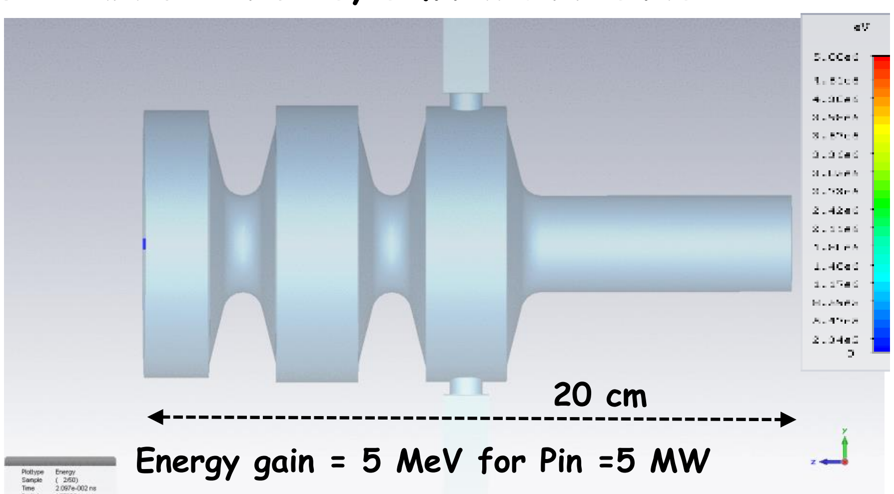
RF power (5 MW)



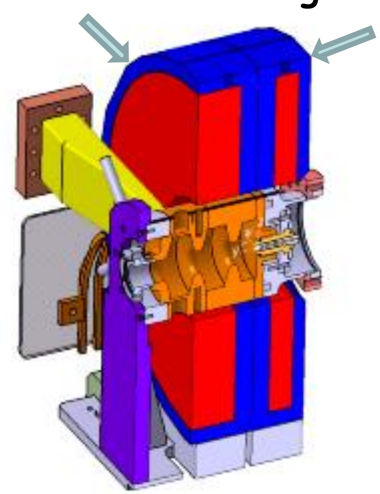
Photoinjector specification

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



new coil configurations



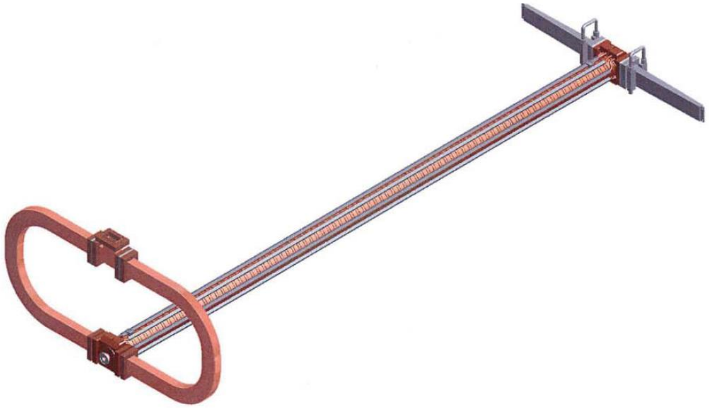
2.5 cells RF gun designed and produced at LAL for ThomX

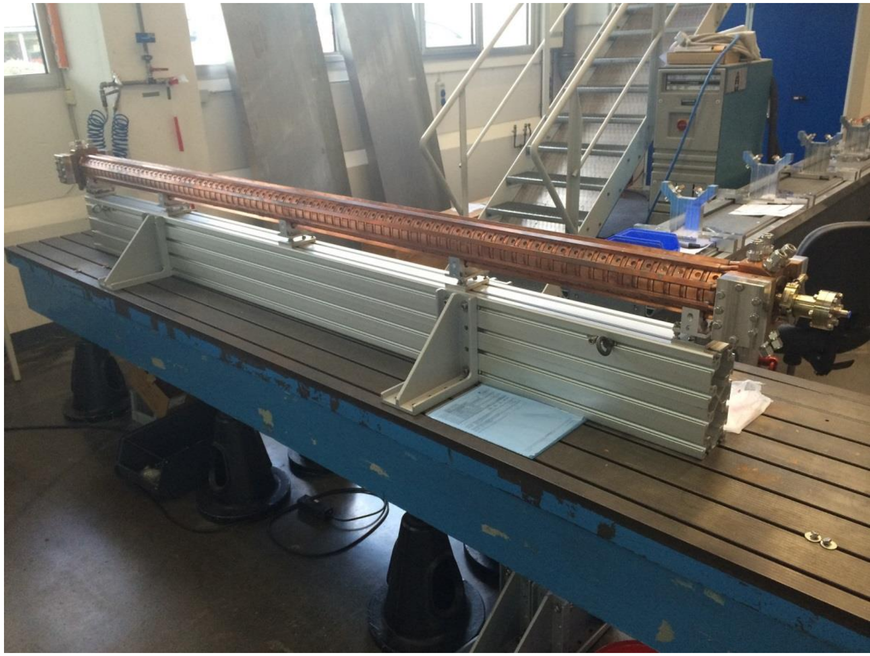
TW S-Band structures from RI

research instruments

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
Guaranteed unloaded energy gain	>65MeV

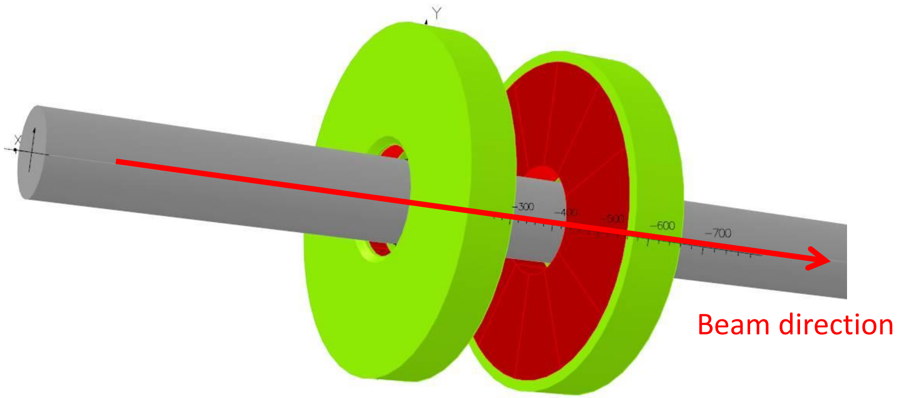
- The Structures **are SLAC-type structures**
- Constant gradient
- Race track coupler for quadrupole compensation
- BIG Splitter for dipole compensation
- 2 RF loads

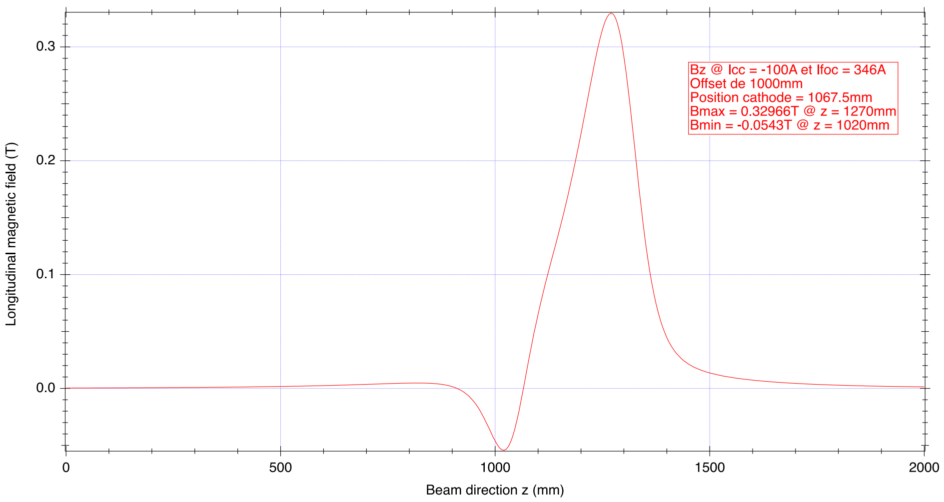




The RF gun solenoids

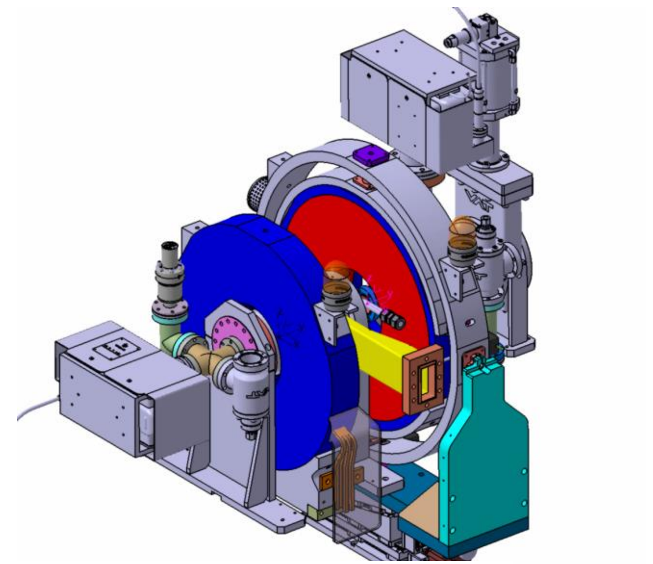
Based on ThomX RF Gun configuration





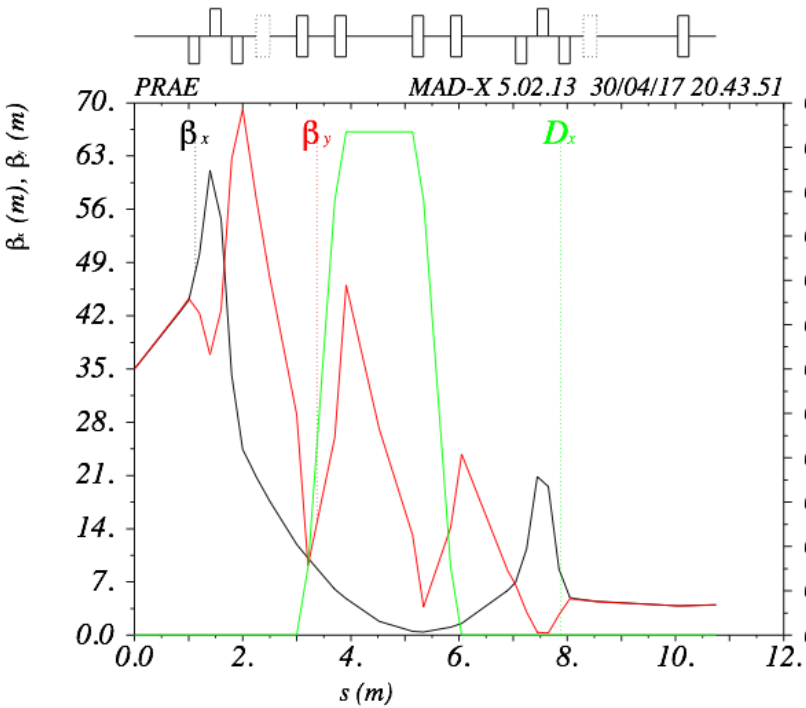
bobine de contre champ	Pour 4 galettes de 21 spires conducteur 6x6t4 2 circuits d'eau courant de 400A			
	pression (bars)	10	15	20
	puissance (W)	12025	11518	11239
	échauffement (°C)	56.91	43.79	36.58
	débit total (l/min)	3.03	3.78	4.41

bobine de focalisation	Pour 8 galettes de 21 spires conducteur 6x6t4 4 circuits d'eau courant de 400A			
	pression (bars)	10	15	20
	puissance (W)	24051	23036	22478
	échauffement (°C)	56.91	43.79	36.58
	débit total (l/min)	6.07	7.55	8.82

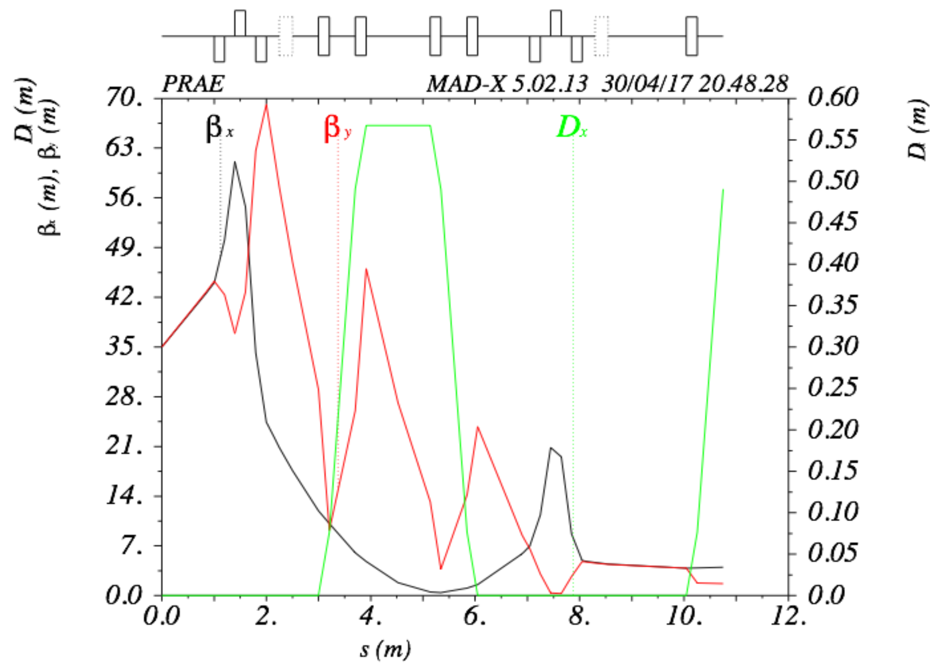


New solenoids configuration

Two triplets, flexible final conditions, with a Energy compression System (ECS) in the direct line and a dedicated Beam Energy Measurement in the deviated line.



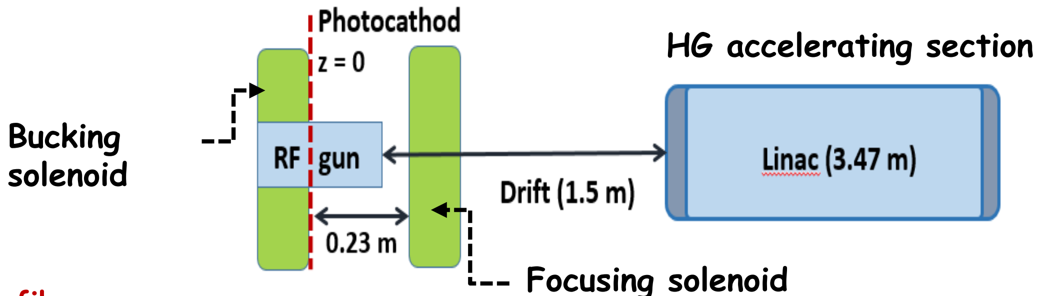
Direct line:
ProRad and Radiobiology



Deviated line:
Instrumentation

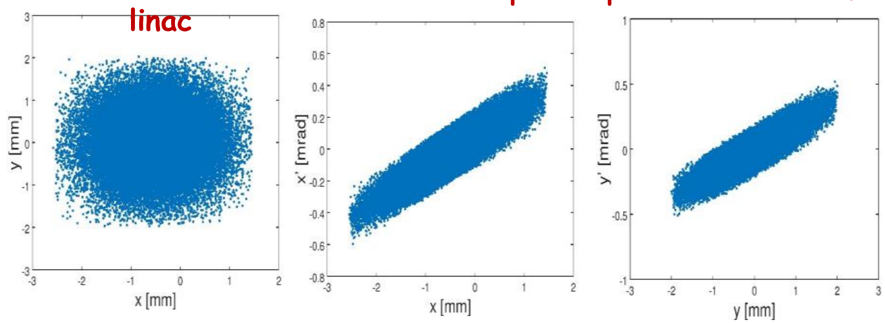
RF-track simulations

- **RF-Track is a novel tracking code developed at CERN for the optimization of low-energy linacs in presence of space-charge effects. The RF structures are described by means of the 3D electromagnetic fields and it is able to treat directly the output of HFSS or CST programs.**
  - **Subsequent calculations are performed using the full 3D EM field** (97 cells) **of the HG accelerating structure generated via CST.**



Beam profiles at the exit of linac

transverse phase space at the exit of linac



Beam performances at the exit of linac

E [MeV]	67
ΔE/E [%]	0.2
$\varepsilon_{x,\ y}$ [mm mrad]	5.31/5.40
$\sigma_{x,\ y}$ [mm]	0.66/0.65
$\beta_{x,y}$ [m]	10.33/10.96

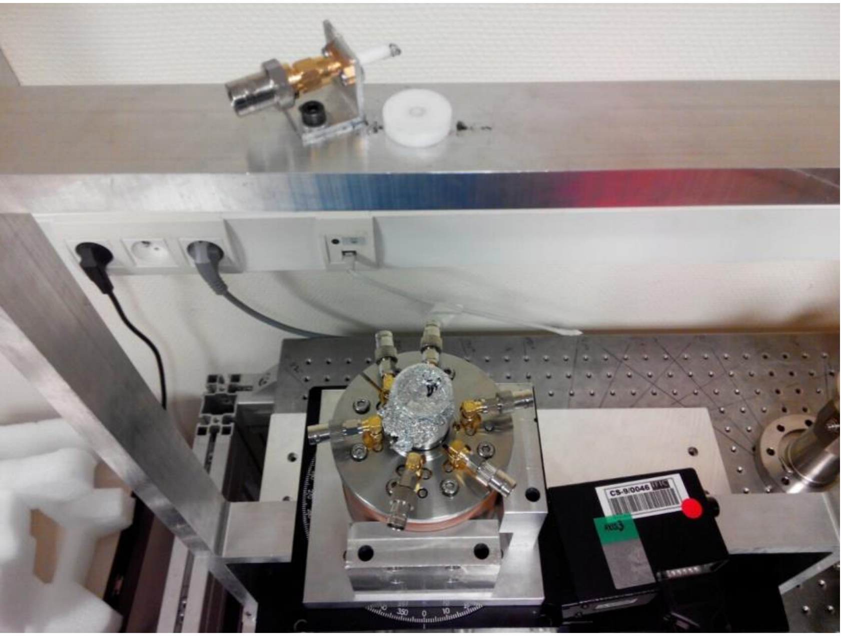
- ➢ **Realistic and reliable result** based on the analysis of the given EM field.
- ➢ The next beam optimization are planned to be performed using the RF track.

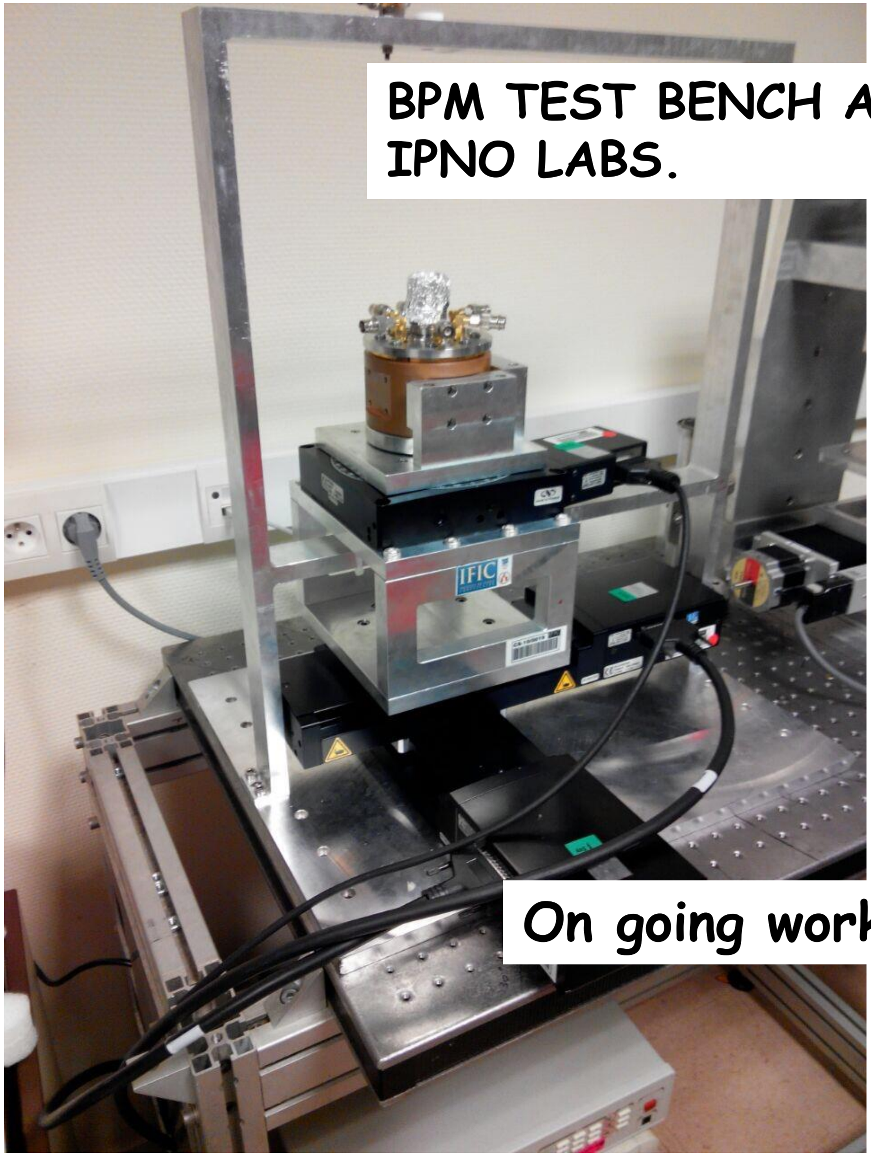
A. Vnuchenko et al, Proceedings of IPAC 2018, Vancouver, Canada

Beam Diagnostics

Inductive BPMs recuperated from CTF3, tests at IPNO in collaboration with BI-CERN

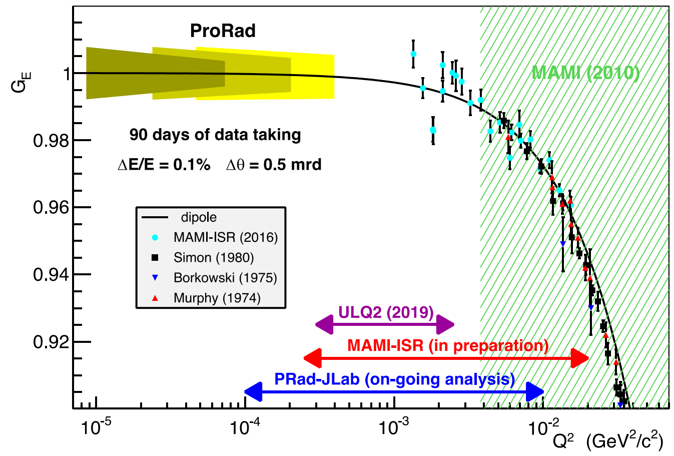
INDUCTIVE BPM





BPM TEST BENCH AT IPNO LABS.

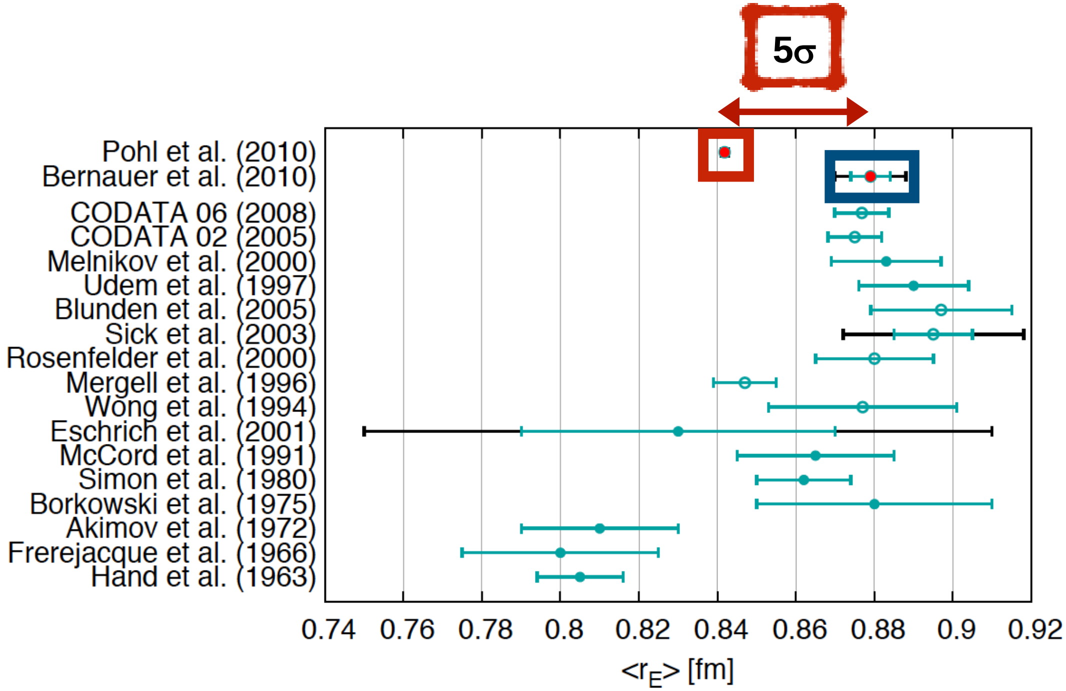
On going work…



The nuclear physics / nucleon structure

- *Principle experiment:* ***proton charge radius measurement, 30-70 MeV***

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

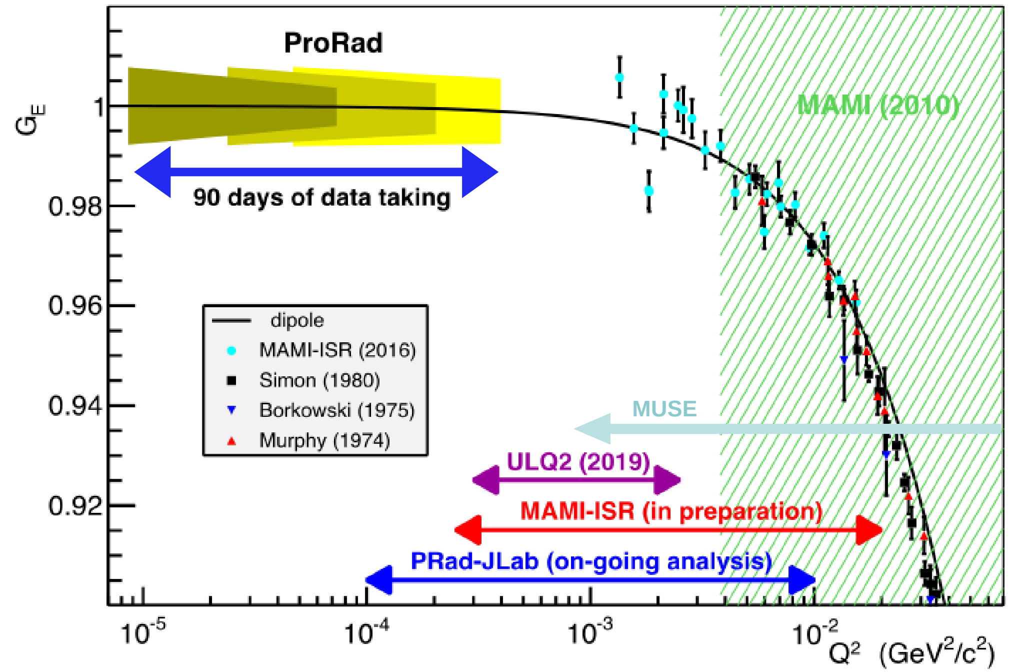
(extrapolation of Form Factor data to Q^2 =0)

→ **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 accelerator experiment requirements:

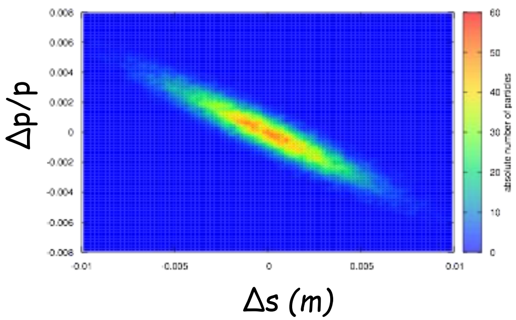
- High precision beam: **reduced energy dispersion** (**5×10^{-4}**)
- Precise knowledge of the **beam energy** (**5×10^{-4}**)

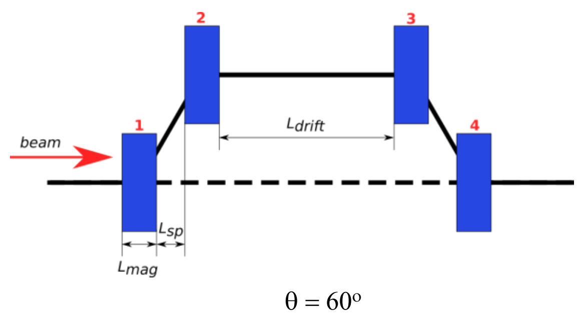
Association with a **RF cavity or dechirping structure**

Energy Compression System

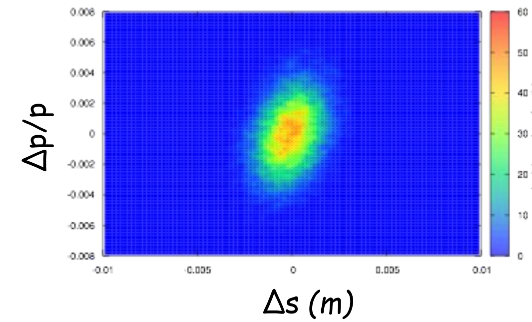
D **chicane** of **4 identical dipoles**

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





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

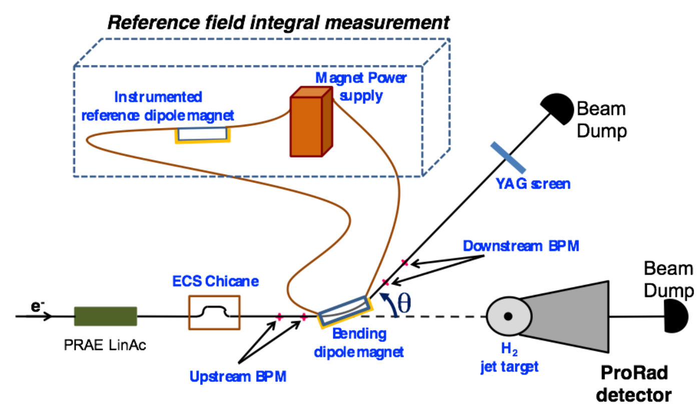


Beam energy measurement

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 **60º deviation angle**



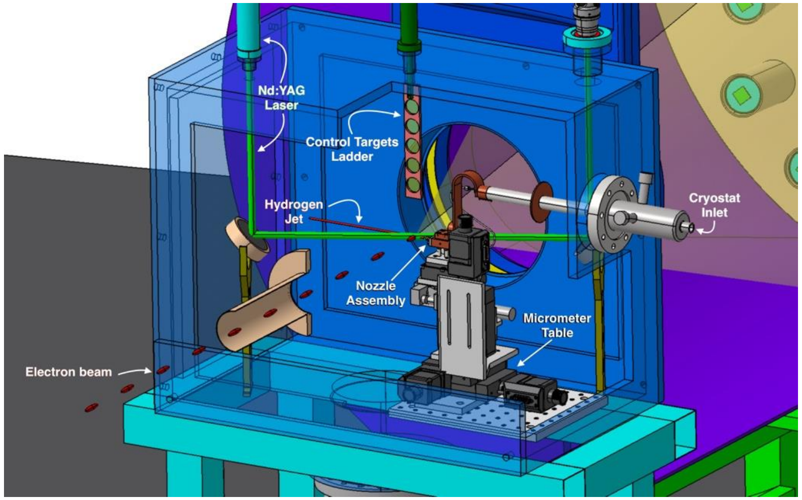
ProRad target experiment requirements:

- A **stable hydrogen target**
- Optimized measurement of the **scattered electron energy** and **position**

French-German collaboration

Hydrogen target

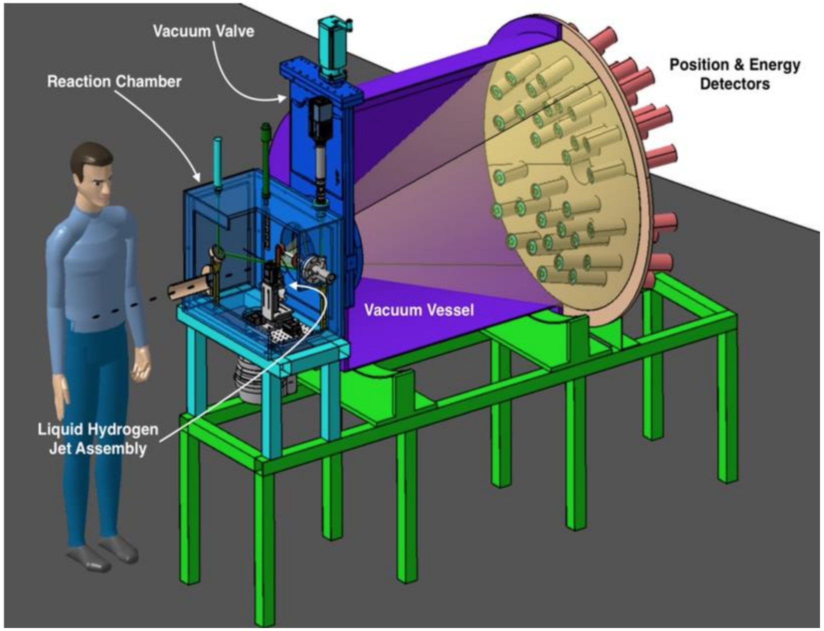
A very **stable windowless** and **self-replenishing** target of **15 μm diameter**



Ultra cold liquid technology developed at Frankfurt University

Reaction chamber with target assembly

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



Instrumentation R&D

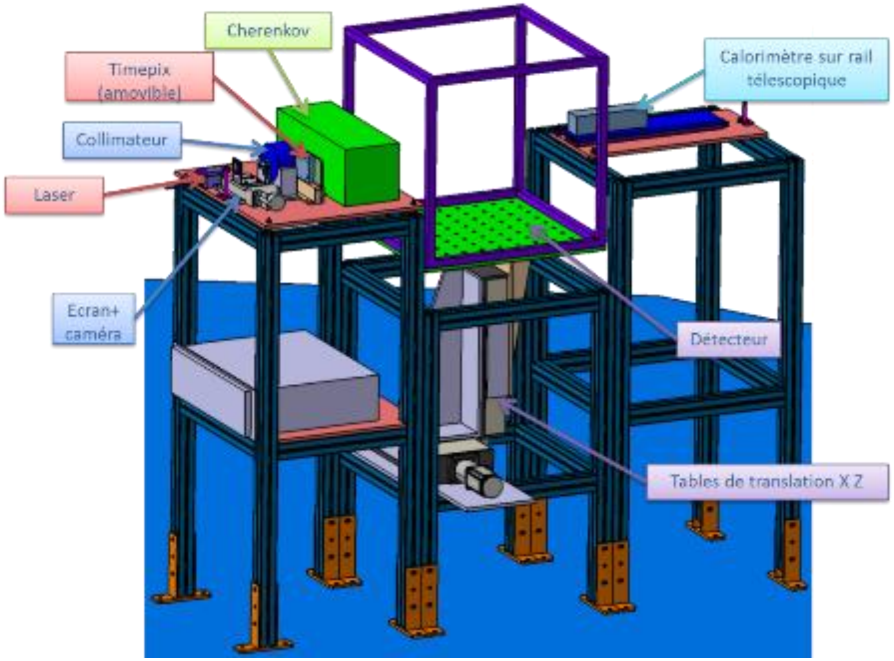
- *Principle goal is to construct versatile tool for detector R&D and tests:* ***deliver calibrated beam with adjusted and known kinematics and number of electrons per sample***

- **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

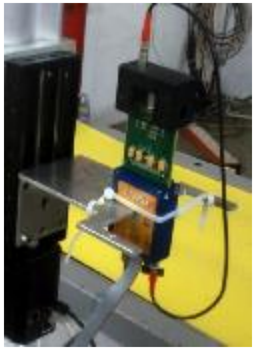
Measure the time, charge and imaging performance of particle detectors

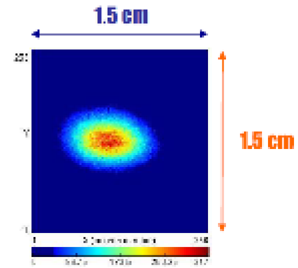
→ *Calibration for charge, trigger, tracking detectors*

Deliverables



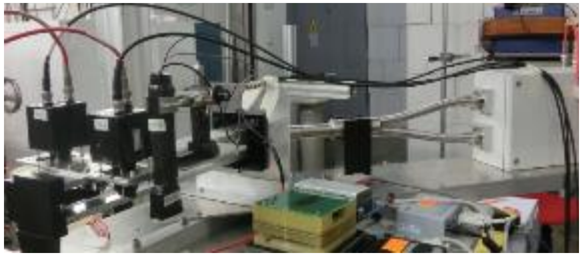
Timepix detector for precision spot measurement

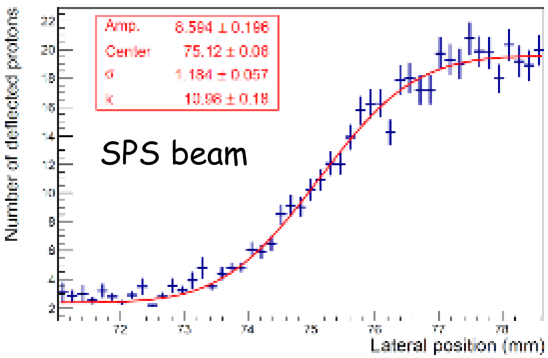




Cherenkov quartz counter for intensity monitoring

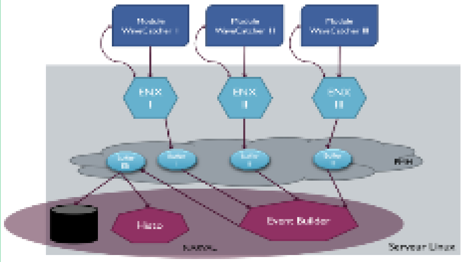
2 channel Cherenkov counters (LAL) tested at BTF (Frascati); installed in the SPS (CERN) beam pipe





DAQ + slow control

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

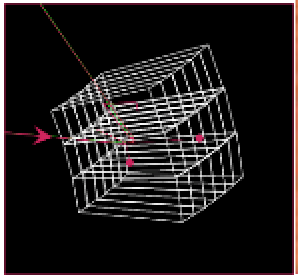


Participation of
Centre de Sciences Nucléaires et de Sciences de la Matière

CSNSM

Calorimeter for energy monitoring

BGO scintillator crystals in compact matrix geometry

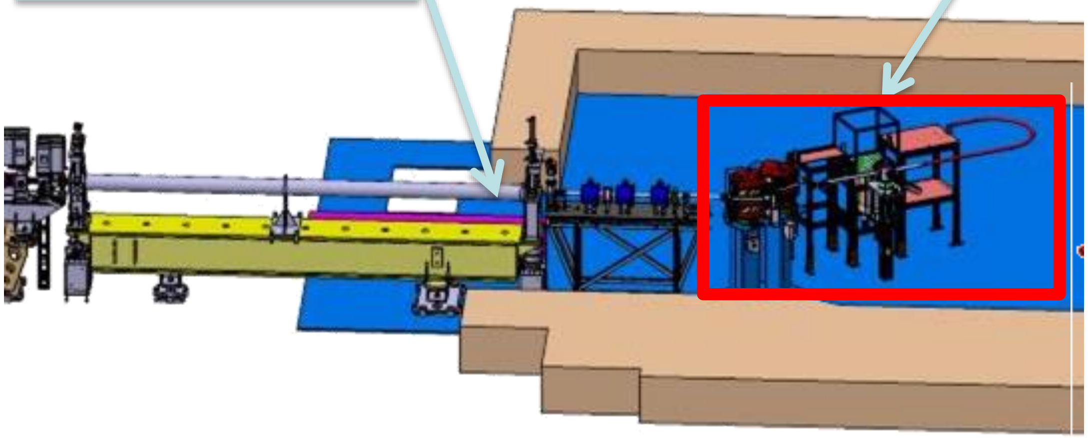


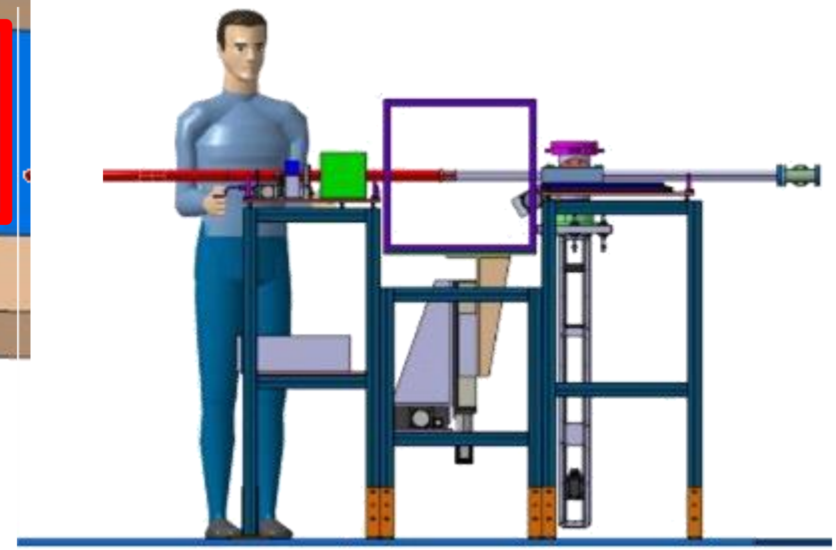
Example of a calorimeter realized at IPN

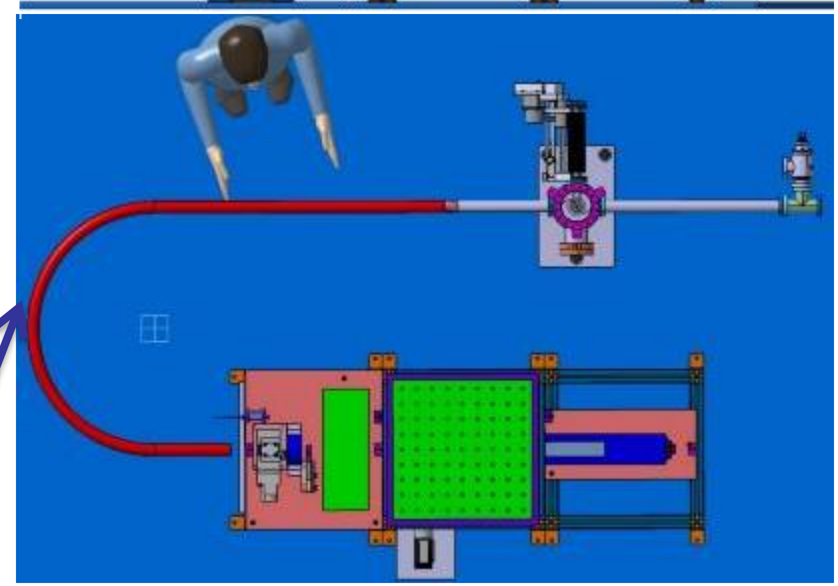
Instrumentation R&D: draft implementation

Accelerator

Platform







SPECTROMETER

The Radiobiology experiment

- *New approaches in radiotherapy: VHEE*
- *Delivery doses:*
  - *Grid mini-neam (Y. Prezado, R. Delorme, IMNC)*
  - *FLASH (V. Fauvadon CPO)*

New approaches in radiotherapy

- Radiotherapy (RT): treatment of some **radio resistant tumors, pediatric cancers** and tumors close to a delicate structure (i.e. spinal cord) is currently **limited**
- One main challenge is to find novel approaches to **increase normal tissue resistance**
- 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 rates ~ 2 Gy/min, field sizes > cm2, homogeneous dose distributions

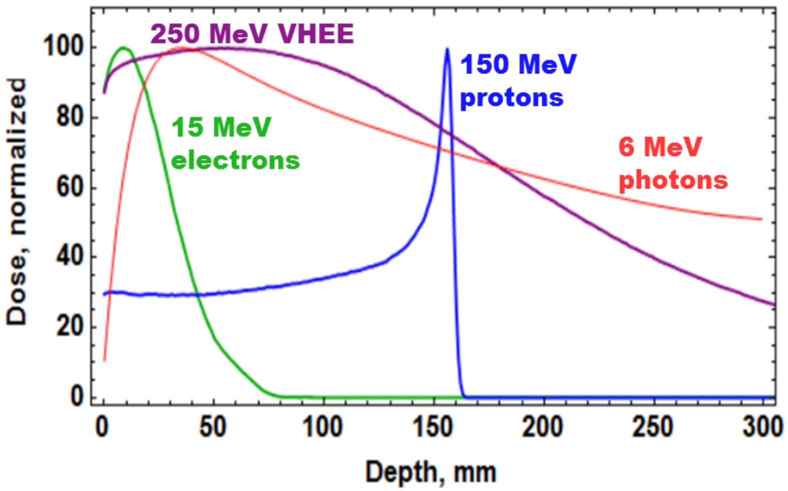
Possible strategies to spare normal tissue

- Different particle types: **Very High Energy Electrons (VHEE)**
- Different dose delivery methods: **Grid Mini-beam or FLASH**

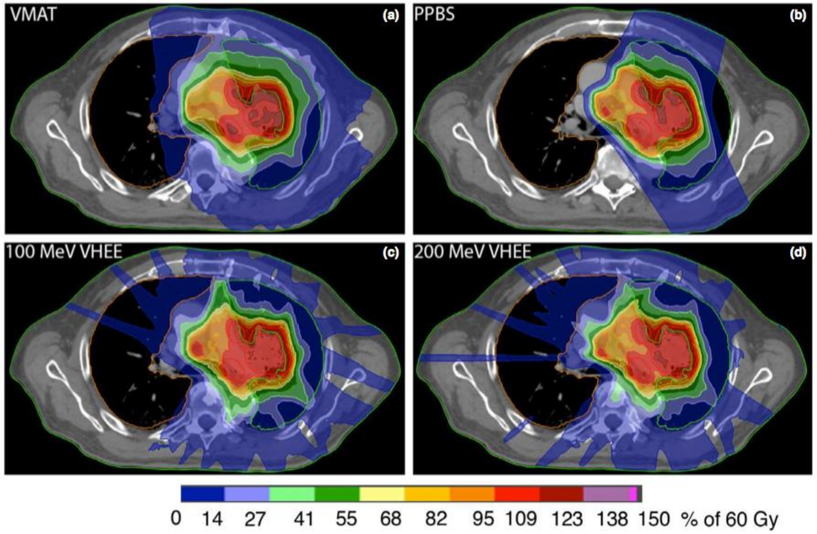
VHEE State of the art:

5-25 MeV electrons are classically used in the clinic but, due to their physical energy deposition profile, their use is restricted to treat superficial tumors. Increasing the energy above 70 MeV (VHEE) will overcome these limitations and, in addition, present the following advantages:

i) the penetration becomes deeper and the transverse penumbra sharper thus allowing a more precise treatment of deeper tumors
ii) the small diameter VHEE beams can be scanned avoiding mechanical solutions such as the multileaf collimator
iii) a rather smaller sensitivity to tissue heterogeneity can be achieved with VHEE beams under certain conditions
iv) VHEE accelerators may be constructed at significantly lower cost than current proton facilities.



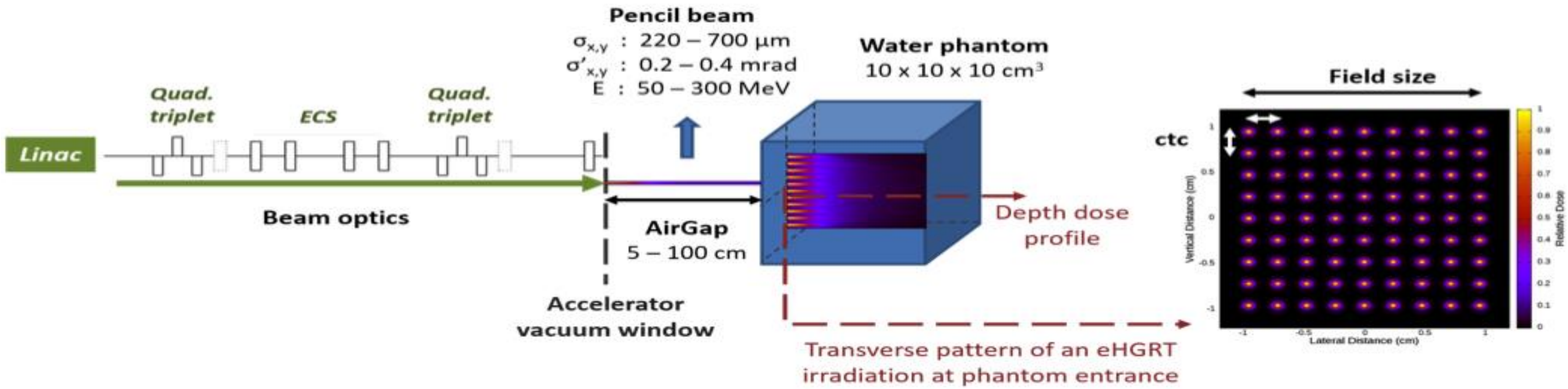
Dose profiles for various particle beams in water (beam widths $r = 0.5$ cm)

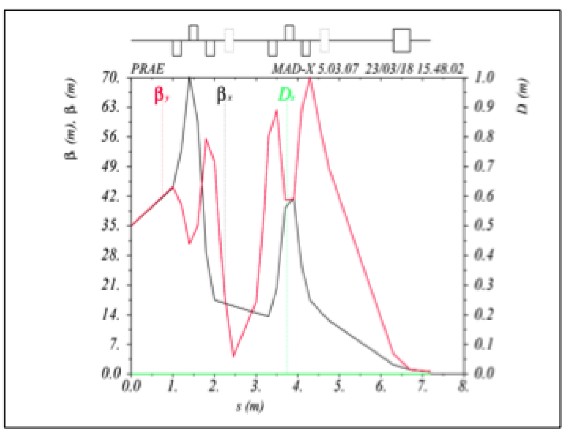


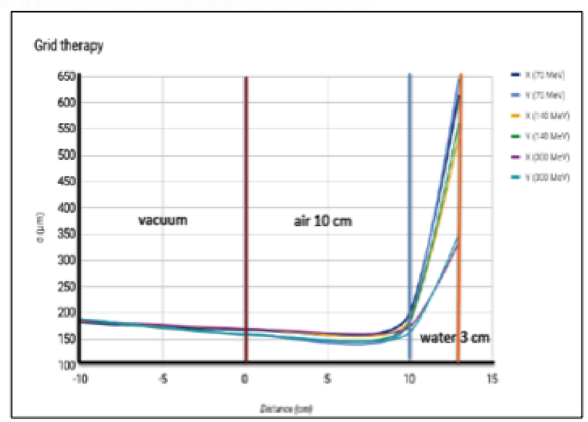
Treatment plan comparison between VHEE, VMAT and PBS

Grid or mini-beam therapy:

One possible strategy to further improve the healthy tissue tolerance by using the concept of Spatially Fractionated Radiation (SFR) dose is the Grid or Mini-Beam Therapy (MBRT). In contrast to conventional RT the lateral dose-profile resulting of such grid-irradiation consist in a pattern of high doses in "peaks " and low doses in "valleys".
First beam optics design to get transverse beam sizes of less than 700 mm with low beam divergence and tracking simulations have been performed.







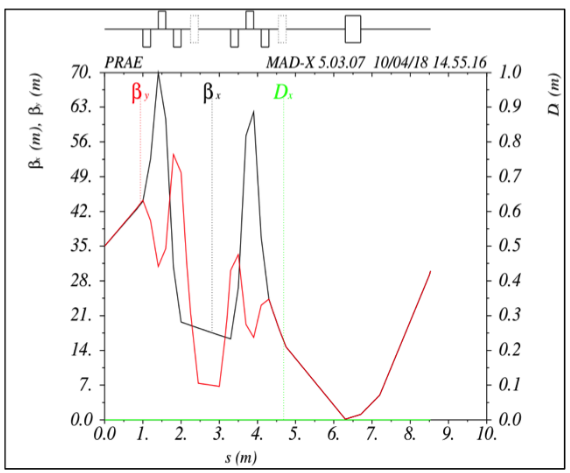
FLASH therapy:

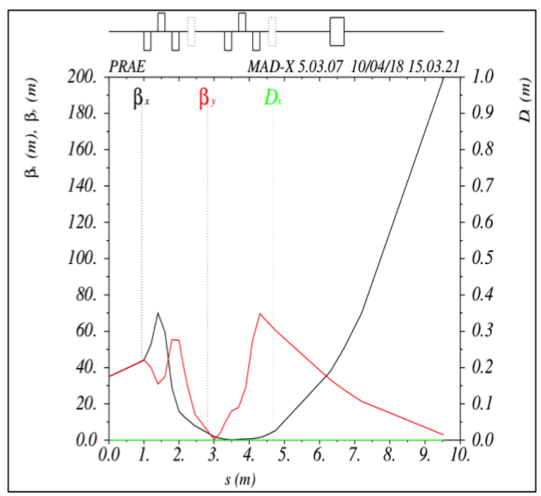
The FLASH methodology consists of millisecond pulses of radiation (beam-on time ≤ 100-500 ms) delivered at a high dose-rate (≥ 40-100 Gy/s), hence over 2000 times faster than in conventional RT. Recently it has been shown that FLASH spares normal brain in mice from the loss of both memory and neural stem cells as endpoints.

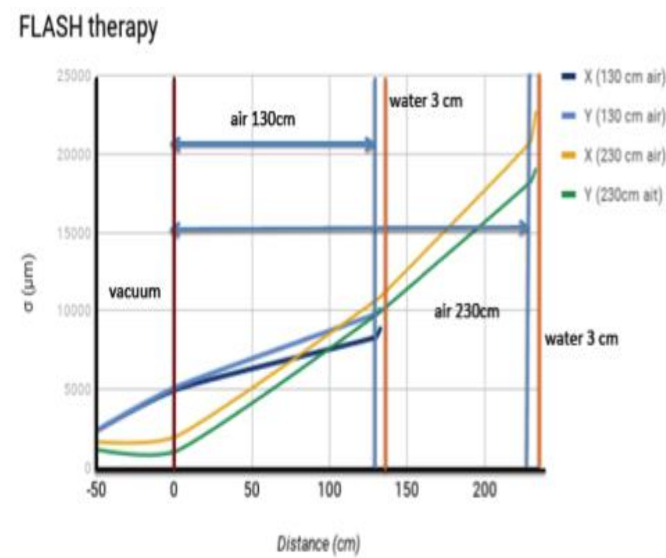
In PRAE direct beam line two different scenarios for FLASH tests in small animals:

i) Sparing brain from radiation-induced loss of stem cells: round transverse beam sizes of around 10 mm with a dose of 10 Gy with beam on time 100 ms (5 bunches at 50 Hz), i.e. 10Gy/s

ii) Sparing lung from radiation-induced fibrosis: transverse beam sizes of around 26 mm in horizontal and 18 in vertical with a dose of 15 Gy with beam on time 500 ms (25 bunches at 50 Hz), i.e. 30 Gy/s.

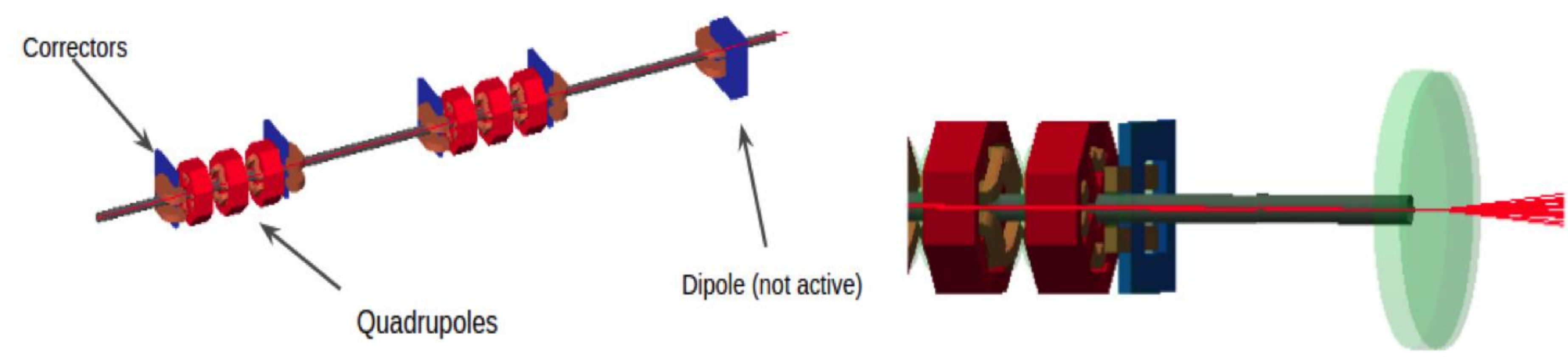


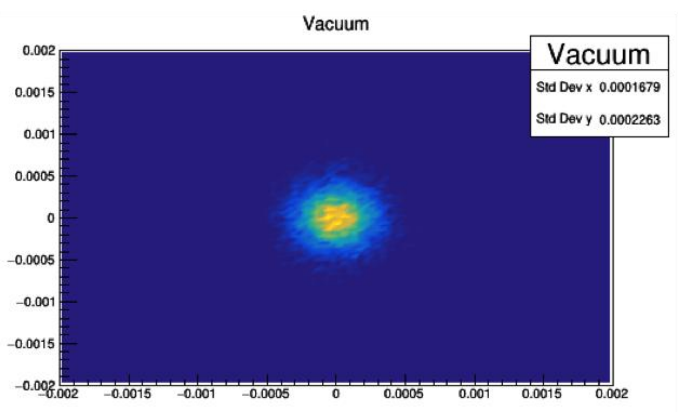


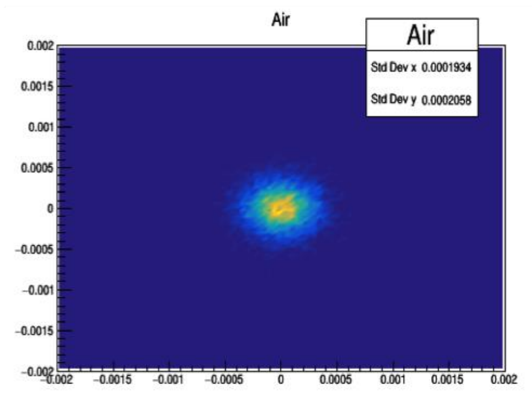


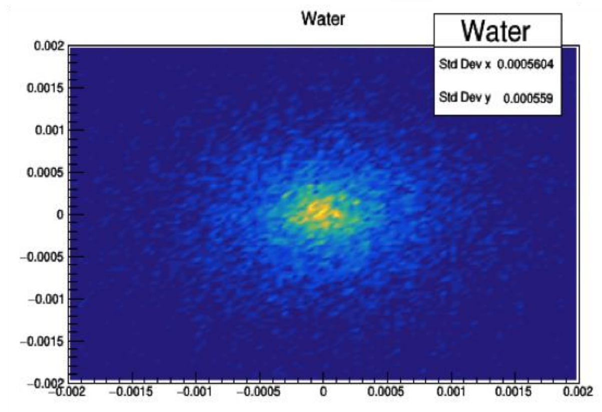
BDSIM simulations : modelling and beam evolution:

Tracking simulations of a Gaussian bunch through the under vacuum accelerator beam line, an air gap of 10 cm and liquid water phantom of 3 cm depth has been performed with a Geant4 (Penelope module) based program BDSIMfor 70, 140 and 300 MeV. A benchmarking of the BDSIM results with MADX for the vacuum part and with the results with GATE (Geant4-based) in air and water has been made.









FEVHER
Feasibility and Experimental Validation of Very High-Energy Electron Radiotherapy

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Angeles Faus-Golfe

Manjit Dosanjh

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22-25 May 18

ARIES 1st Meeting

Motivation and Objectives:

The main goal of FEVHER project is to demonstrate that VHEE are suitable for innovative RT applications in particular by allowing Grid and FLASH methodologies, which are likely to represent a major breakthrough in RT.

CNRS, University of Manchester, Institute Curie, CERN

- Adaptation and Exploitation of the existing Facilities
- Medical Physics: Modelling and Dosimetry
- In Vitro Radiobiolo gy
- In Vivo and pre-Clinical studies
- Design of an optimized future machine for VHEE

Beam performances of CLEAR, VELA-CLARA and PRAE

CLIC-CERN U. MANCHESTER CNRS-LAL

Beam parameters (end of linac)	**CLEAR**	**VELA-CLARA**	**PRAE**	***Units***
Energy	130 - 220	50 - 250	70 - 140	*MeV*
Bunch charge	0.01 - 0.5	0.02 – 0.250	0.00005-2	*nC*
Normalized emittances	3/20 for 0.05/0.4 nC	~1	3-10	*mm*
Bunch length	500 - 1200	15 - 600	<300	*mm*
Relative energy spread	< 0.2 %	<0.03 %	<0.2%	
Repetition rate	1 - 5 (25 upgrade)	1 – 100	50	*Hz*
Number of micro-bunches in train	1- >100	1	1	
Micro-bunch spacing	1.5			*GHz*

- Task 3.4 is progressing well

- A dedicated session for others applications of e- up to 140 MeV could be organized in the PRAE workshop in Fall 2018