7^{th} ADAMAS workshop
13^{th} - 14^{th} December 2017

Fast Diamond Detectors for Beam Tagging Applications in Hadrontherapy

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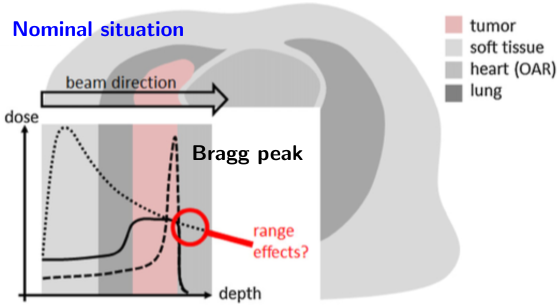
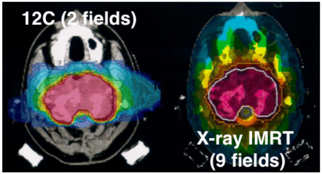
Advantages and pitfalls in hadrontherapy

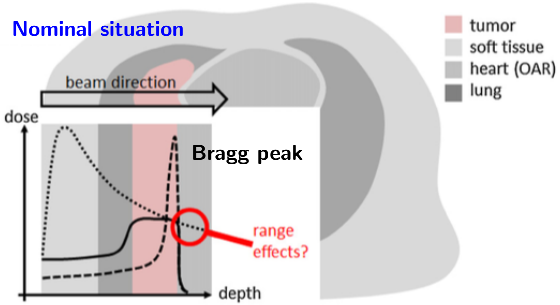


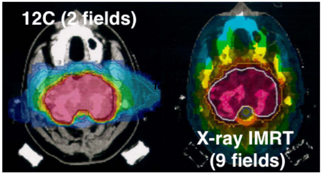


Amaldi and Kraft, Rep Prog Phys 2005

Advantages and pitfalls in hadrontherapy

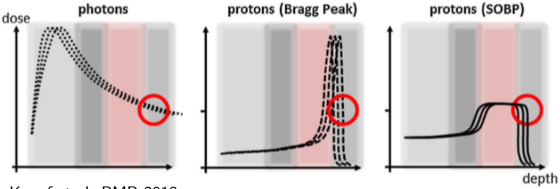
Nominal situation





Amaldi and Kraft, Rep Prog Phys 2005

Actual situation



Knopf et al. PMB 2013

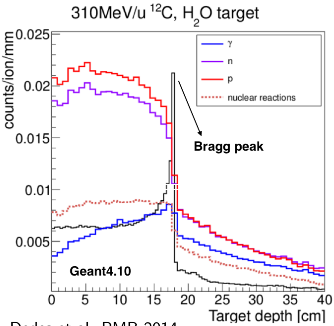
Need for on-line range verification

Range monitoring with prompt gammas

Prompt gammas

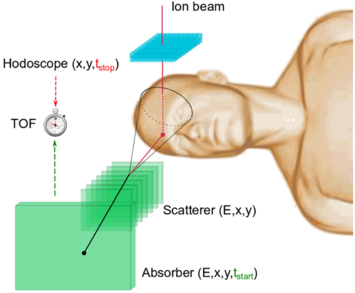
Emitted by nuclear de-excitation following NN collisions in the patient

- nearly isotropic
- $0 < E_\gamma < 10$ MeV
- emission within < 1 ps



Dedes et al. PMB 2014

Compton camera CLaRyS (IPNL, CPPM, LPC, LPSC)



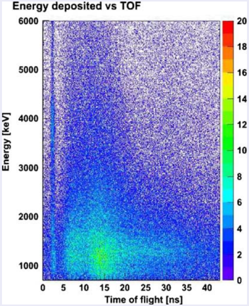
Hodoscope:

- Incident ion (bunch) position (reconstruction of the PG emission point)
- Incident ion (bunch) arrival time (TOF)

TOF detection of prompt gammas

Background reduction (increased sensibility)

95 MeV/u ^{12}C beam on PMMA target
(BaF_2 at d>50cm from target)



M Testa et al. Rad Env Bio 2010

TOF resolution $\sim$ 1 ns required

TOF detection of prompt gammas

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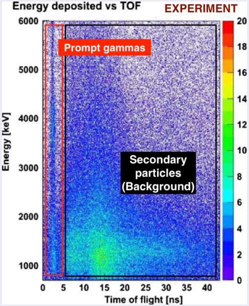

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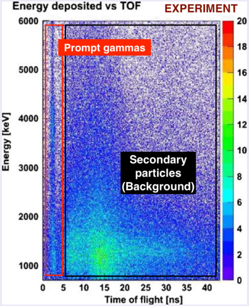


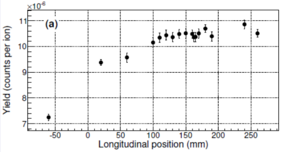
M Testa et al. Rad Env Bio 2010

TOF resolution ∼ 1 ns required

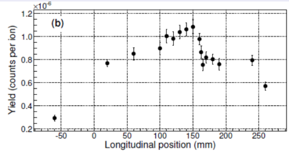
Necessary for ^{12}C treatment

300 MeV/u ^{12}C beam on PMMA target

Prompt gamma profiles **WITHOUT** TOF



Prompt gamma profiles **WITH** TOF



M Pinto et al. New J Phys 2015

TOF detection of prompt gammas

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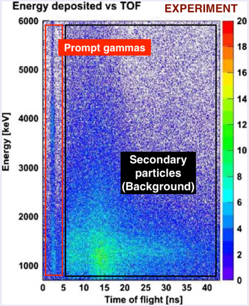

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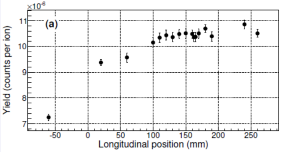
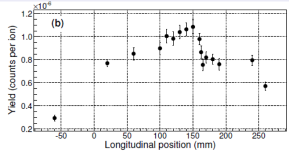


Prompt gamma profiles **WITH** TOF



M Pinto et al. New J Phys 2015

An external detector is necessary for multi-energy treatment (RF varies phase!).

High-resolution TOF detection of prompt gammas

A little bit of kinematics . . .

A 200 MeV proton travels at $\sim$ c/2

A 100 ps TOF resolution allows determining the γ vertex within 1.5 cm

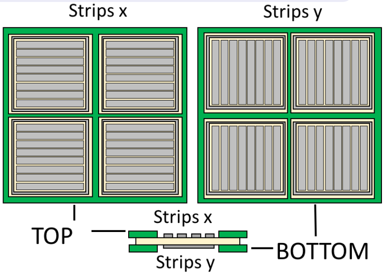
$\rightarrow$ Higher SNR expected

$\rightarrow$ No reconstruction needed for Compton imaging (Real Time !)

On-going development at LPSC: diamond-based hodoscope

Specifications:

- Time resolution $\sim$ 100 ps
- Count rate $\sim$ 10 MHz per channel
- Spatial resolution $\sim$ 1 mm
- Radiation resistant



Protontherapy (Cyclotron IBA/C230)

$\sim$ 2 ns bunch every 10 ns

200 p/bunch $\rightarrow$ **Bunch tagging**

Carbontherapy (Synchrotron)

$\sim$ 30 ns bunch every 200 ns

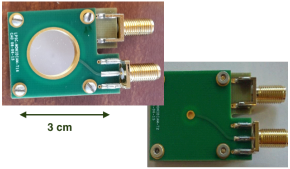
10 ions/bunch $\rightarrow$ **Ion tagging**

Characterisation of diamond detectors

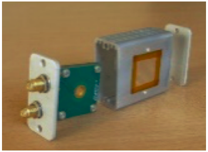
Available samples

sc-CVD	sc-HPHT	DOI	pc-CVD
E6	**NDT**	**AuDiaTec**	**E6**
5x5 mm^2 x 3	5x5 mm^2 multisector x 1	5x5 mm^2 x 3	10x10 mm^2 x 5
	3x2.5 mm^2 monosector x 1	10x10 mm^2 x 2	20x20 mm^2 x 1
			II-VI
			10x10 mm^2 x 1

50 Ω adapted PCBs

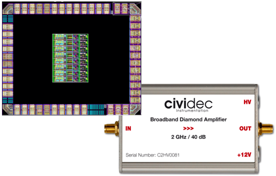


EM shielding box



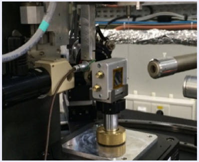
Readout electronics:

(CIVIDEC for single channel custom for multi-channel)



Detector surface analysis with XBIC - single channel diamonds at 500 V

Mimic the interaction of single particles



8.5 keV X-rays

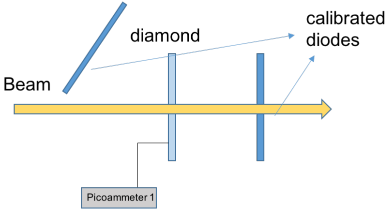
1 μm spot

1500 photons/bunch

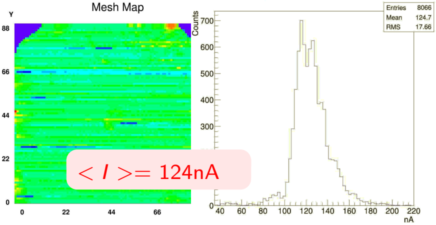
Bunch width = 100 ps

Edep $\sim$ 3.3 MeV max

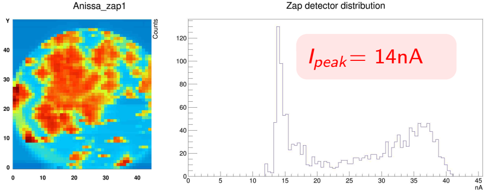
2D detector scans at $\sim$40 μm steps



5x5 mm^2 x 500 μm sc-CVD from E6



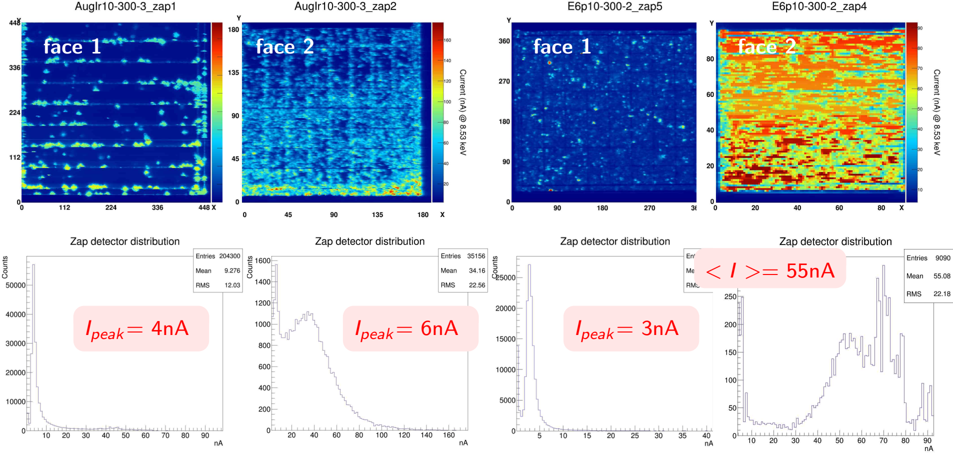
5x5 mm^2 x 300 μm DOI from AuDiaTec



Works perfectly despite heterogeneous response

Detector surface analysis with XBIC - stripped diamonds at 300 V

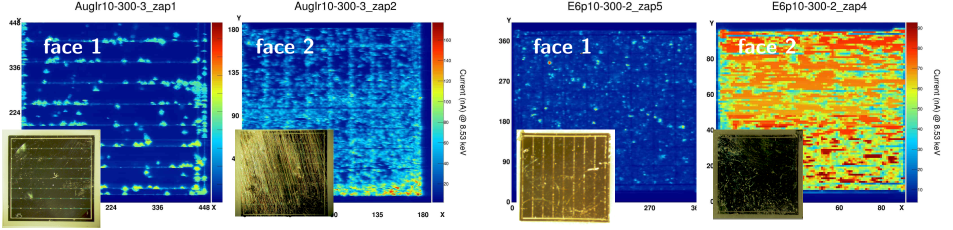
1x1 cm^2 x 300 μm DOI from AuDiaTec **1x1 cm^2 x 300 μm pc-CVD from E6**

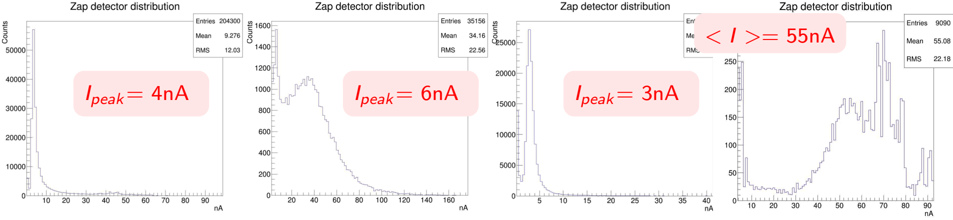


- current response seems related to surface defects
- DOI and pc-CVD showed the same current response

Detector surface analysis with XBIC - stripped diamonds at 300 V

1x1 cm^2 x 300 μm DOI from AuDiaTec | **1x1 cm^2 x 300 μm pc-CVD from E6**





- current response seems related to surface defects
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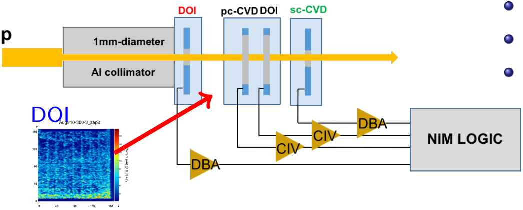
Diamond detection efficiency



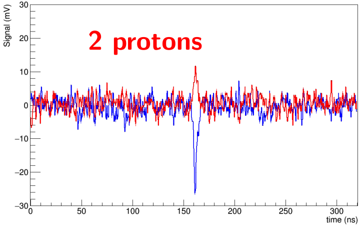
Triple/double coincidences

- Beam intensity = 1 pA (< 1p/bunch)
- 1 p signals selected on external detector
- Variable thresholds on DOI and pc-CVD

Detection efficiency:

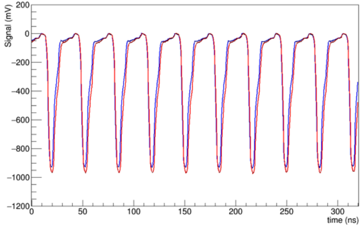
= 0.3% – 40% for DOI
= 75% – 90% for pc-CVD

Low intensity 160 fA
($<<$ 1 p/pulse)

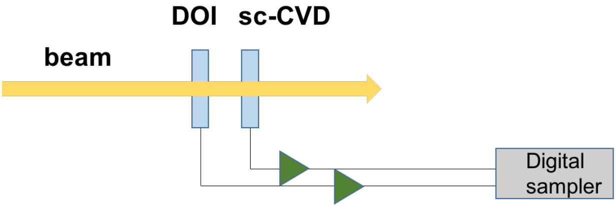


pc-CVD 1 cm^2
DOI 1 cm^2

High intensity 25 nA
(5000 p/pulse → attenuated signal)



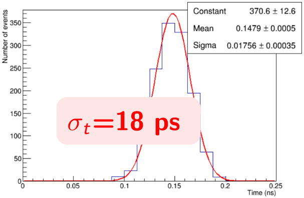
Diamond time resolution - penetrating radiation



Single crystal
sc-CVD E6
$0.45 \times 0.45\ cm^2 \times 518\ \mu m$

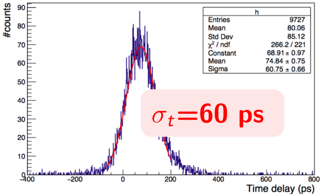
Heteropitaxial DOI
DOI Augsburg
$0.5 \times 0.5\ cm^2 \times 300\ \mu m$

95 MeV/u ^{12}C at GANIL



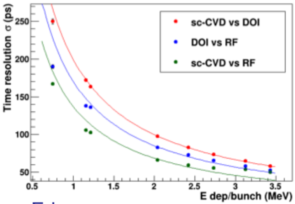
Edep
= 25 MeV in DOI
= 44 MeV in sc-CVD

68 MeV protons at ARRONAX



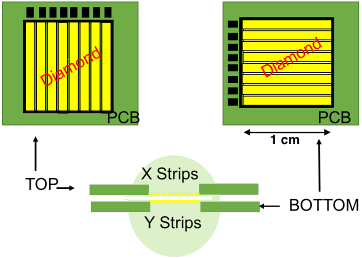
Edep
= 1.2 MeV in DOI
= 1.8 MeV in sc-CVD

XBIC source at ESRF

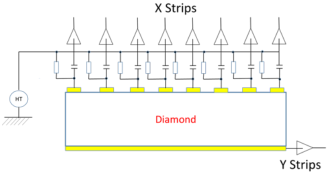


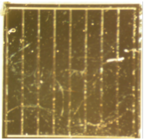
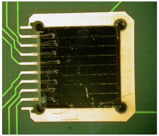
Edep
= 0.7 – 3.4 MeV in DOI
= 0.7 – 3.3 MeV in sc-CVD

Characterisation of stripped detectors

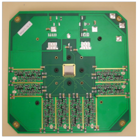


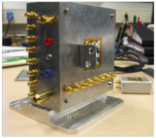
Lateral view



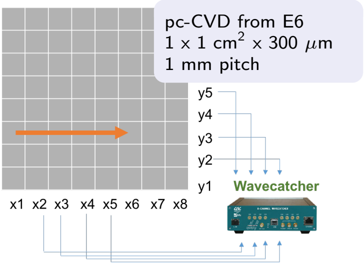
NANOFAB Néel Institut Grenoble



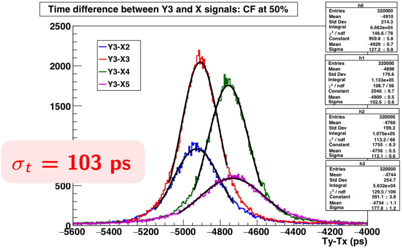


LPSC Grenoble

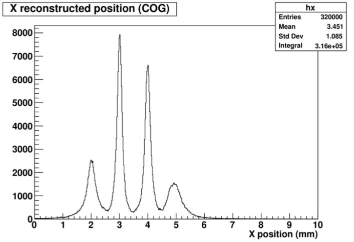
Detector scanning with XBIC source (100μm step - Edep $\sim$3.3 MeV)



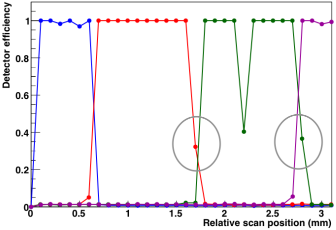
TOF resolution: X vx Y strips



COG reconstructed X position



Strip detection efficiency

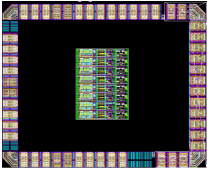


On going development: front-end microelectronics

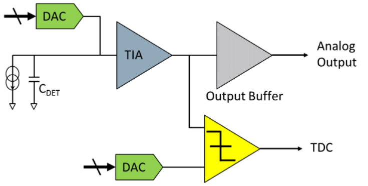
130 nm CMOS TIA + Fast discriminator

- Radhard technology
- Wide bandwidth, low noise TIA
- 8 channels: V1 submitted Jan. 2018, V2 Nov. 2018

1.485 x 1.2 mm^2

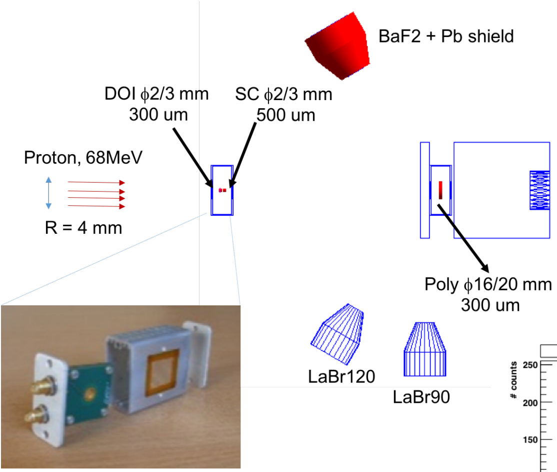


TIA Parameters	Value
A_0	> 60 dB
F_{-3dB}	1.2 GHz
Z_{in}	20 - 50 Ω
$V_{n,out}$ (output range)	< 1 mV_{RMS}
Input Dynamic range	3 μA - 120 μA
	(non-linearity <1%)



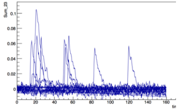
1 channel FEE

A fast beam tagging hodoscope for range monitoring in hadrontherapy

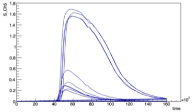


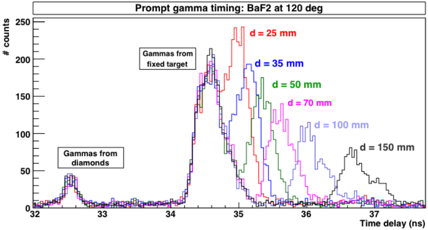
- Detector signals sampled with Wavecatcher (3.2 Gs/s)
- Trigger on one gamma detector

DOI signal



LaBr signal

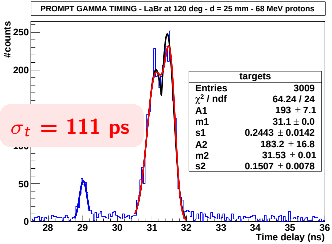




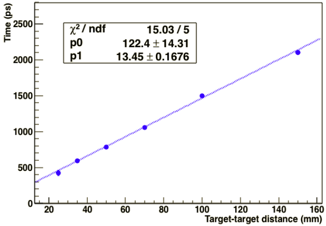
Aim: exploit the-ultra fast coincidence time to detect range variations due to target heterogeneities

Beam test results

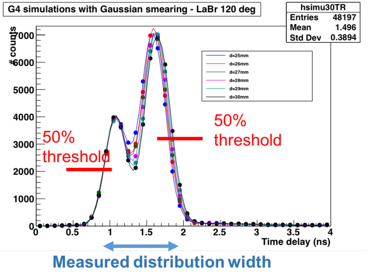
Experiment: PG timing spectrum



Target heterogeneity thickness: measured vs actual value



MC simulations for sensibility assessment



Beam test results

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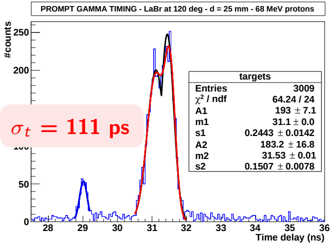
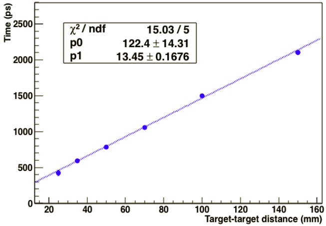


$\sigma_t = 111$ ps

Target heterogeneity thickness: measured vs actual value



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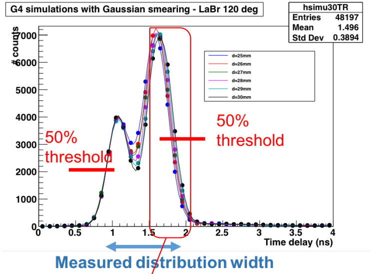
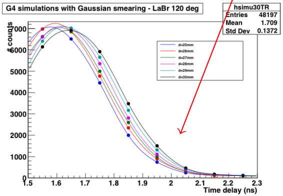


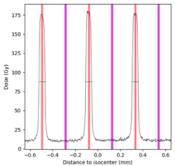


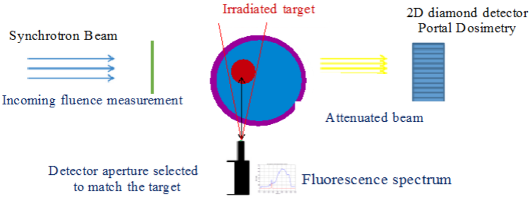
For 1 irradiation spot:

- 4 mm shift detectable at 3σ
- 2 mm shift detectable at 1σ

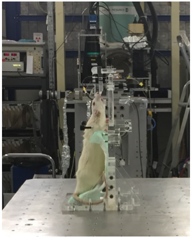
Diamond dosimeter for micro-beam radiotherapy at ESRF

MRT: 50 μm beamlets

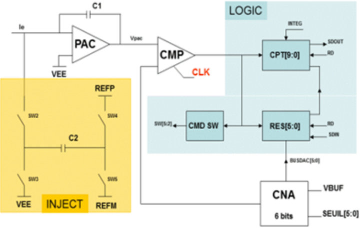




First test September 2018 during animal irradiation



Development of dedicated QDC



Conclusions and perspectives

- Main goal: fast timing for charged particles with large area detectors

- Characterization of the performances of small and medium size detectors with sources, ions, and synchrotron
- Multi-strip detectors: a first prototype of 1 cm2 has been developed and tested with discrete electronics
- Experiments proved excellent timing resolution

- Issue: Large area diamond with high detection efficiency for protons hardly available

Next steps . . .

- NDT and II-VI diamonds to be tested
- Micro-electronics readout under development

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Additional slides

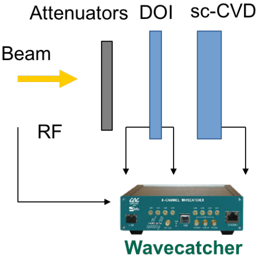
Beam temporal structure

		synchrotron		cyclotron (C230, IBA)	cyclotron Varian	synchro-cyclotron (S2C2, IBA)
		^{12}C	Protons			
Typical intensity (ions/s)		10^7	10^9	10^{10}	$10^8 - 10^{10}$	$\sim 10^{10}$
Macrostruct.	Period (s)	$1 - 10$		$\varnothing$		10^{-3}
Microstruct.	Bunch width (ns)	$20 - 50$		$1 - 2$	0.5	8
	Period (ns)	$100 - 200$		10	14	16
	Ions/bunch	$2 - 5$		200	$2 - 200$	4000

- Synchrotron and synchro-cyclotron: low duty cycle, favorable for PET
- Cyclotron: very short pulses, favorable for TOF-PG

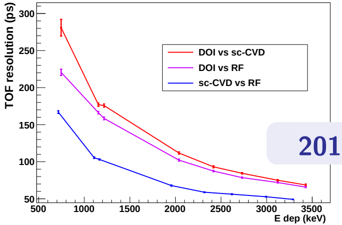
- Possibility of a reduced beam intensity at the beginning of the treatment// (tagging of each ion)

TOF resolution with attenuated XBIC source



- Time resolution degrades as SNR lowers
- Possible to stay below 150 ps σ at low deposited energies

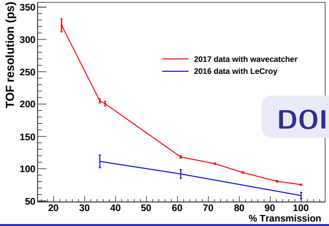
TOF resolution: DOI vs sc-CVD



2017 data

Noise level assessment

two beam tests, same irradiation conditions, different detectors



DOI vs DOI