Readout Electronics for a Proton Computed Tomography Apparatus

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MOTIVATIONS FOR pCT

Stopping powers are the main parameters for dose calculation in proton radiotherapy. They are derived from measured attenuation coefficients $\mu$ of conventional xCT.

The error intrinsic in this conversion (due to $\mu(\eta_e, Z)$ dependency on atomic number and electron density) is the principal cause of proton range indetermination (3%, up to 10 mm in the head)

[Schneider U. (1994), Med Phys. 22, 353]

Main aim of pCT: direct measurement of stopping power...

...and, possibly:
- a. Lower dose to the patient, with respect to xCT (according to MC simulations).
- b. Increase of low-contrast resolution
- c. Patient positioning before every treatment
MAIN DIFFICULTY WITH pCT: multiple Coulomb scattering

To obtain high space and energy accuracy:

1. determination of protons Most Likely Path (MLP)

2. single proton tracking

Entrance and exit angles and positions are boundary conditions for MLP calculation.

200 MeV Protons, 20 cm water
Most Likely, $1\sigma$ and $2\sigma$ path
CONCEPT
BACKGROUND

Initial studies with a Si single-sided strip telescope by UCSC and LLUMC.

Use of Si detectors (194 μm pitch, 400 μm thickness) to measure:
  a) protons trajectory;
  b) energy loss, from time over threshold (TOT).

Limits:
  1) slow acquisition rate (1kHz).
  2) Low energy resolution (25% at 250 MeV), improved in a later prototype by a separate calorimeter.

COLLABORATION AIMS

1) realize a high-performance prototype for proton radiography

<table>
<thead>
<tr>
<th>Proton Energy</th>
<th>250-270 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton rate</td>
<td>$\sim 10^6$ 1/sec</td>
</tr>
<tr>
<td>Space resolution</td>
<td>&lt; 1 mm</td>
</tr>
<tr>
<td>electron density resolution</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>&gt; 1000 Gy</td>
</tr>
</tbody>
</table>

2) validate the prototype with pre-clinical studies
3) conceive a configuration for a pCT system.

Research supported by:
INFN (Natl. Inst. of Nucl. Phys.), "PRIMA" experiment
MIUR (Dept. of University and Research) PRIN 2006 funding
Tracker Module

Front End board

Tracker digital Board

Microstrip sensor

ASIC (x8)

DAC

256

256

8+2

256

DO

Test

control bus

address bus

data bus

Ethernet Unit

FPGA

S-RAM (4)

1MBx16

Trigger

Trigger_en

GEN

8

8+2

2

Test

control bus

address bus

data bus

Ethernet Unit

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8+2

2

Test
Si SENSOR

- 53x53 mm²
- p+-on-n strips
- 256 ch, 200 µm pitch
- 200 µm thickness

tradoff between energy loss and sensitivity
Si SENSOR PERFORMANCES

Sensor Depletion Voltage (from C-V)

- $V_{fd} < 75 \, V$
- $i(100V) < 1 \, \mu A$
- $i(200V) < 3 \, \mu A$
- $C = 54 \, \text{pF/cm (coupling)}$
- $C = 1.5 \, \text{pF/cm (interstrip)}$
ASIC design

6.6 x 1.6 mm²
32 inputs - 32 outputs
670 mW power consumption
Vcc=+3.3 V

Single channel

Charge Sensitive Amplifier
Differentiator (high pass)
I Integrator (low pass)
II Integrator (low pass)
Comparator
External threshold voltage
Buffer

Single strip

OUT
ASIC CAD SIMULATION: output signal

Rise time = 12ns @ CL = 30pF
Fall time = 13ns @ CL = 30pF
Width ~ [250 + 0.50×E(keV)] ns
Dynamic range ~ 3 MeV
X-Y PLANE ASSEMBLY

Front end board
ASICs
Routing strips
Microstrip detector
Connector
Tracker digital board
Digital electronics

S-RAM blocks

FPGA

Ethernet unit

Other I/O
Calorimeter

Charge spectra for 62 MeV proton beam

The relationship between the input energy beam and the peak position

The relationship between the input energy beam and the resolution

YAG:Ce properties

<table>
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<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Physical properties</td>
<td></td>
</tr>
<tr>
<td>Density [g/cm$^3$]</td>
<td>4.57</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>No</td>
</tr>
<tr>
<td>Chemical formula</td>
<td>Y$_3$Al$<em>5$O$</em>{12}$</td>
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<tr>
<td>Luminescence properties</td>
<td></td>
</tr>
<tr>
<td>Wavelength of max. emission [nm]</td>
<td>550</td>
</tr>
<tr>
<td>Decay constant [ns]</td>
<td>70</td>
</tr>
<tr>
<td>Photon yield at 300K [10$^3$ Ph/MeV]</td>
<td>40-50</td>
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Y3Al5O12 Chemical formula

No Hygroscopic

4.57 Density [g/cm$^3$]

The relationship between the input energy beam and the resolution

Good for high-energy

The relationship between the input energy beam and the peak position

FWHM Resolution %
Final calorimeter layout to be realized in 2007
CALORIMETER READOUT DESIGN

Tracker modules

Trigger Generator

UF2-4000 14 bit Digitizer/Oscilloscope

Calorimeter front-end

AO 1-4

Calorimeter front-end

Calorimeter front-end

Calorimeter front-end

Trigger

8

Vth'

Monostable

Trigger_en

Σ

Tracker modules
TIMING

[Image of a timing diagram with labels and annotations]

### TELESCOPE DEVELOPMENT PROGRESS

|----------------------|----------|--------|------------|------|-------------|--------|------------|--------------|------------------------|----------------------------|

<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>Crystals</th>
<th>Purchased</th>
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<td>Test &amp; debug</td>
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</table>

| DAC board            | Purchased |          |            |      |             |        |            |              |                        |                            |

<table>
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<tr>
<th>Software</th>
<th>FPGA</th>
<th>Development</th>
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<th></th>
<th></th>
<th>Preliminary versions available during Nov. 2007.</th>
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<tr>
<td>DAC board</td>
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Assembling of 1st tracker module: dec. 2007

Test with calorimeter: during 2008.

Assembling of the full telescope: dec. 2008
CONCLUSIONS

The construction of a pCT system has been approached

A telescope has been designed:
- SSD Si tracker;
- YAG:Ce segmented calorimeter.

Electronics characteristics:
- 1 MHz event rate.
- 32 ch readout ASICs designed within the collaboration;
- control and data acquisition by FPGA circuits;
- trigger generation from calorimeter data;
- pre-triggered calorimeter waveforms acquisition (precise energy loss meas.)
- possible energy loss in silicon measured by TOT.

Milestones
- Dec. 2008: assembling and test of the full telescope.
- Dec. 2008: design of the pCT system.