Dose Delivery Instrumentation

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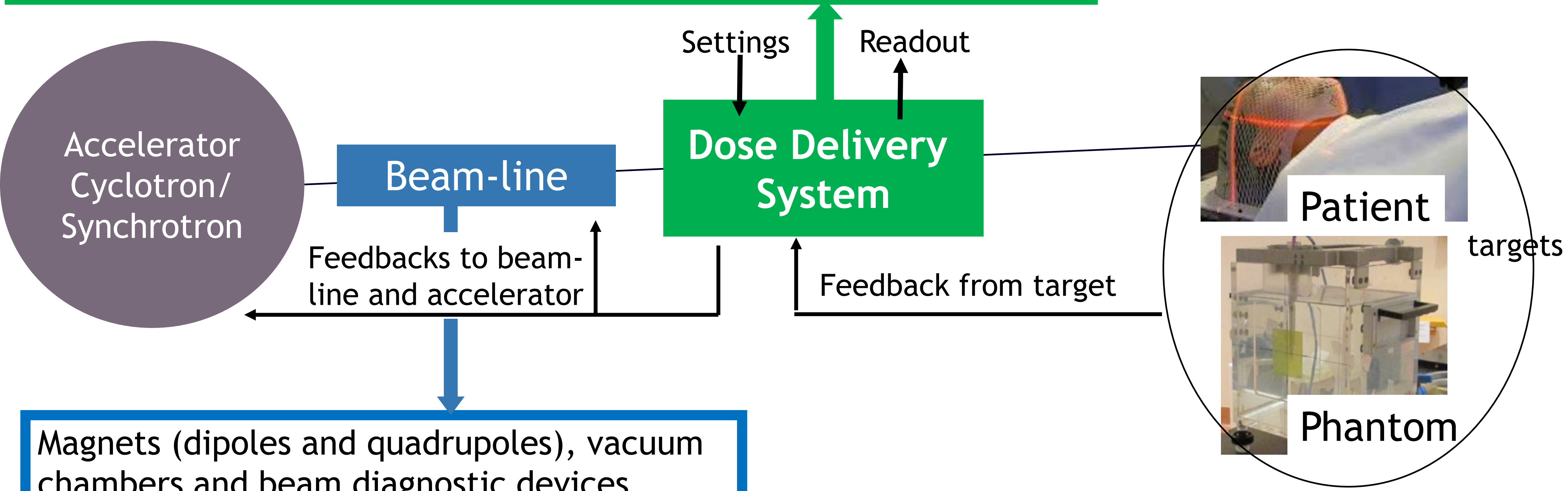
Where is and acts the Dose Delivery System?

Schematic of principle

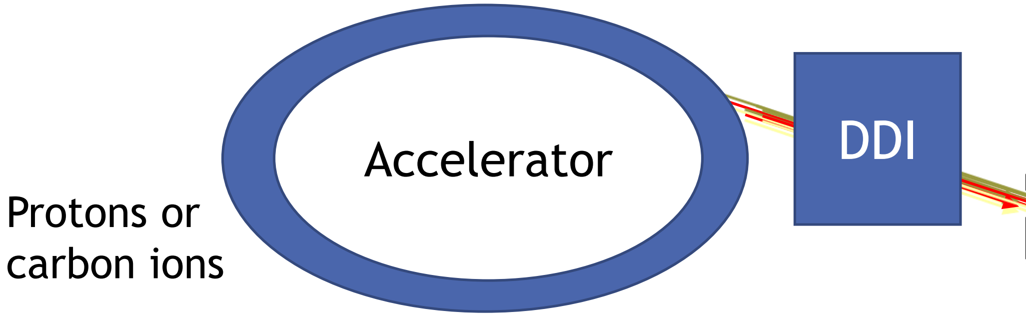
DD Instrumentations to **control** and **modify** the beam just before the patient → **DD includes beam MONITORS and perform the TREATMENT management**

Some instruments are
in vacuum → on the beam line
or in air → on the nozzle

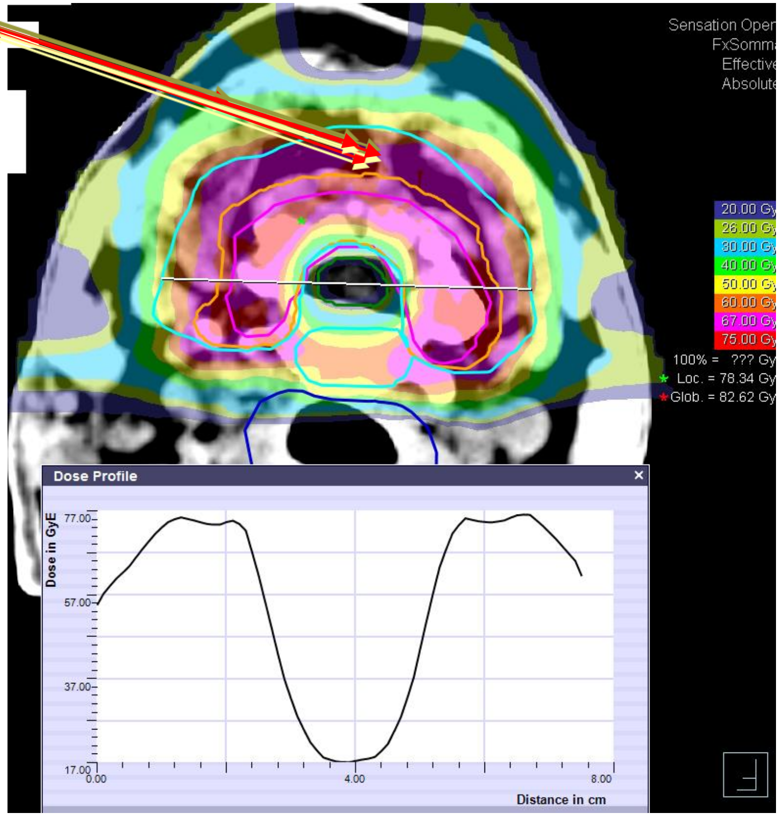


Magnets (dipoles and quadrupoles), vacuum chambers and beam diagnostic devices

DD provides the “right Beam” following specifications based on clinical requirements



Clinical goal



Which is the role of the DD instrumentation?

At the highest level, the goals of radiotherapy are to

→ Deliver the required dose

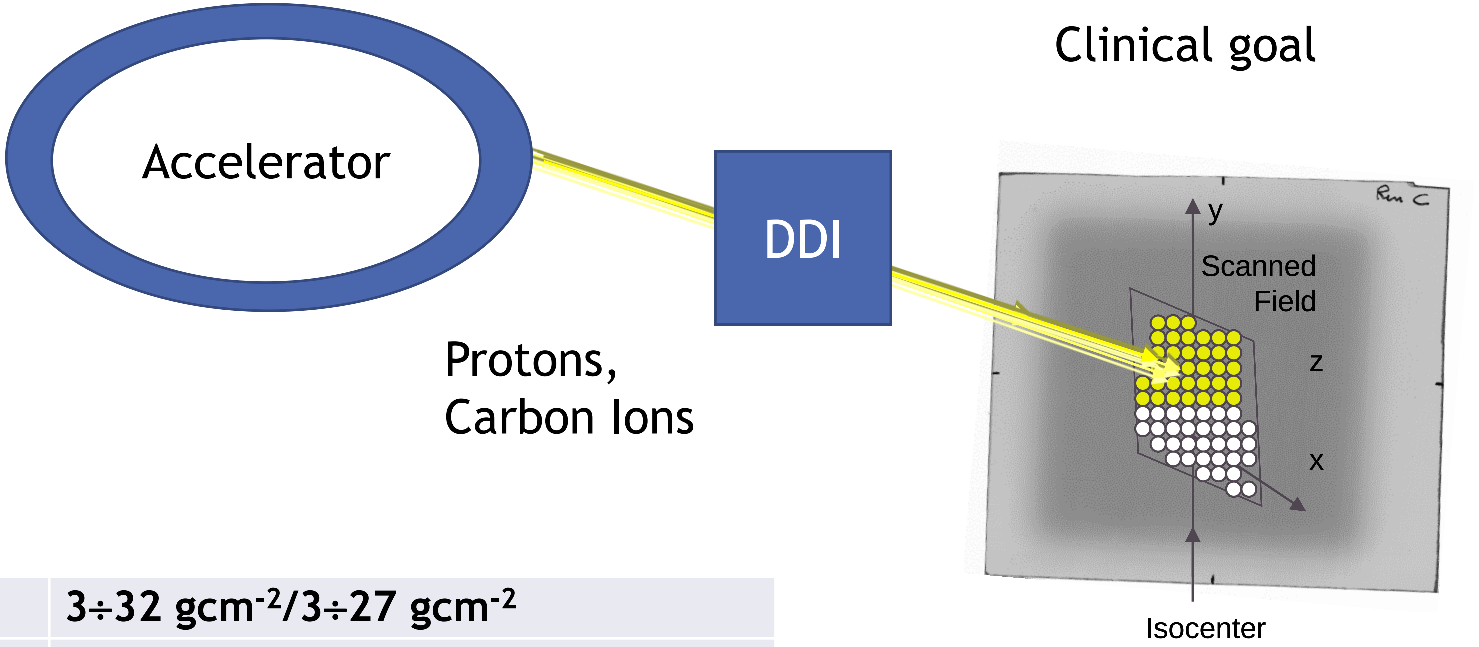
→ Deliver that dose with the prescribed dose distribution

→ Deliver that dose in the right place

→ Deliver that dose in an acceptable time

Beam Specifications based on Clinical Requirements

The nominal beams available at the vacuum exit window of the accelerator have to be adapted to the specific patient and tumor



Accelerator

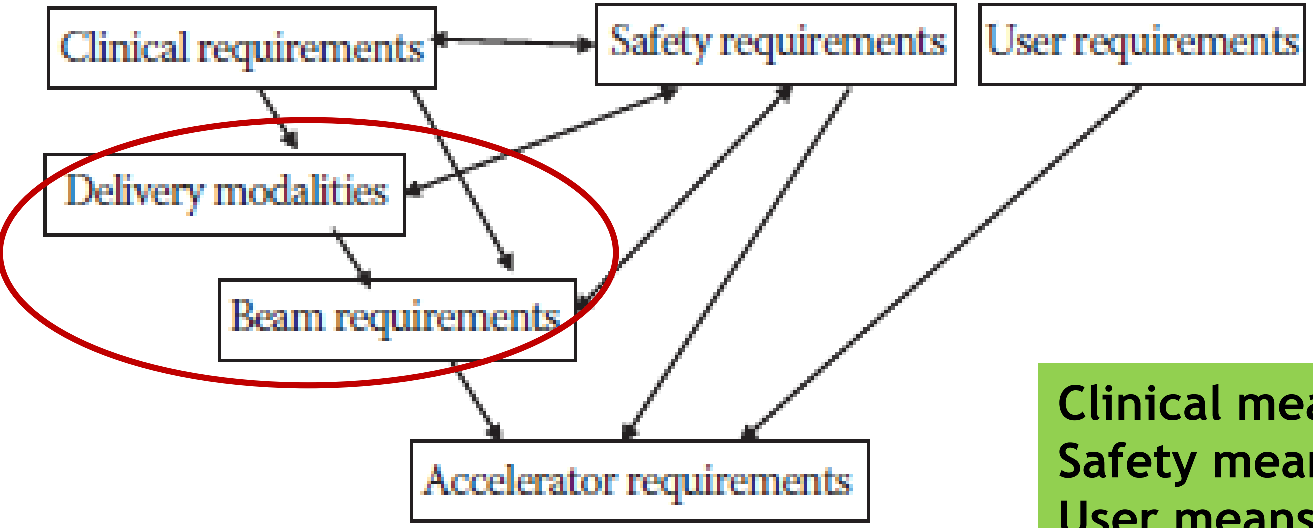
DDI

Protons,
Carbon Ions

Clinical goal

Beam range for protons/carbon ions	$3 \div 32$ gcm^{-2}/$3 \div 27$ gcm^{-2}
Beam energy range for protons/carbon ions	60÷250 MeV / 120÷400 MeV/u
Min÷Max beam intensity for protons/carbon ions	$10^8 \div 10^{10}$ / $4\times10^7 \div 4\times10^8$ per sec
Spot size (FWHM in air at the isocenter) protons/carbon ions	7÷20 /4÷8 mm from highest to lowest energies
Min / Max field size	20x20/40×40 cm^2 at the isocenter

Flow of requirements



Clinical requirements

Safety requirements

User requirements

Delivery modalities

Beam requirements

Accelerator requirements

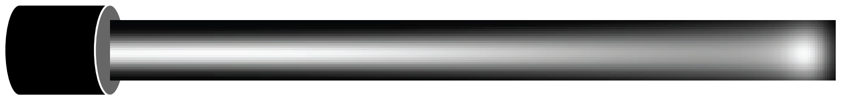
The **clinical, safety and user** requirements affect the beam requirements → DDI technical specifications

Clinical means → ACCURATE, STABLE, CHEAP
Safety means → ROBUST, SIMPLE, REDUNDANT, CERTIFIED
User means → PRACTICAL, FRIENDLY, NOT PATIENT DEPENDENT
… if possible

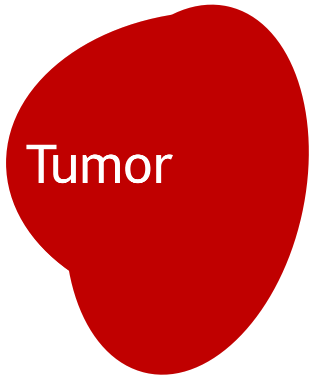
DDI requirements depend on:

Delivery modality → Scattering ≠ Wobbling ≠ Scanning
Accelerator → Cyclotron ≠ Synchrotron
Treated pathologies → Tumor dimension 3x3x3 cm^3 ≠ 25x20x10 cm^3
Particles used → Only synchrotron and scanning technique for carbon ions

DDI to SPREAD the BEAM



FWHM 2 ÷ 10 mm

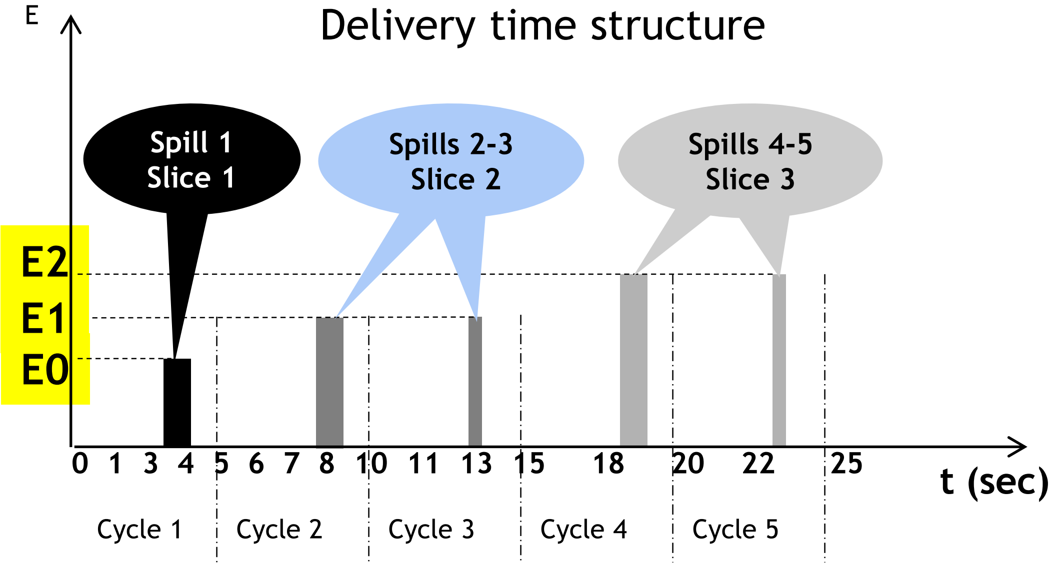


Target dimension: 1 ÷ 50 cm

Cyclotron vs synchrotron: different beam energy variation (different DDI for dose modulation in depth)

Synchrotron beams

The energy can be varied spill by spill to adapt range and
using ripple filters and small energy steps
it performs the required energy/depth modulation (SOBP)



Cyclotron beams

Picture by M. Schippers (PSI)

fast degrader
at cyclotron exit (PSI)

: 5 mm ΔRange in 100 ms

Fixed beam energy

To SET the beam range:
-> Fast degrader
-> Range shifters

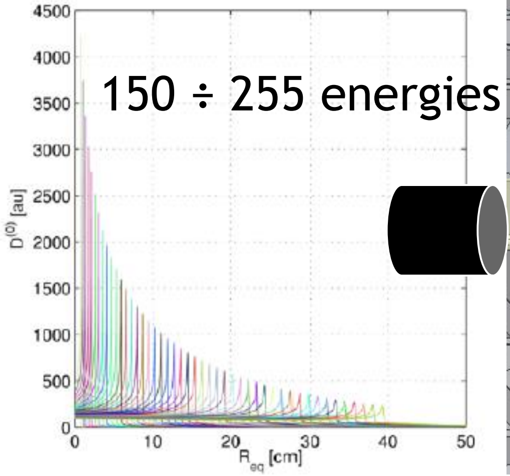
If the degrader is fast enough it performs the energy modulation (SOBP)

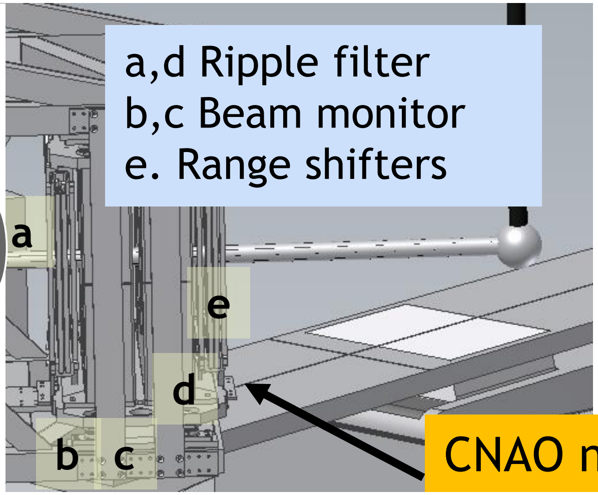
Different synchrotron operations: examples

HIT – CNAO – MedAustron synchrotron

The Synchrotron energy resolution allows 1 to 2 mm step in depth → ΔE ~ 0.5 MeV/u to 2 MeV/u for protons at ~ 230 and ~ 60 MeV respectively

Only ripple filters
(1 or 2) to spread out the Bragg peak



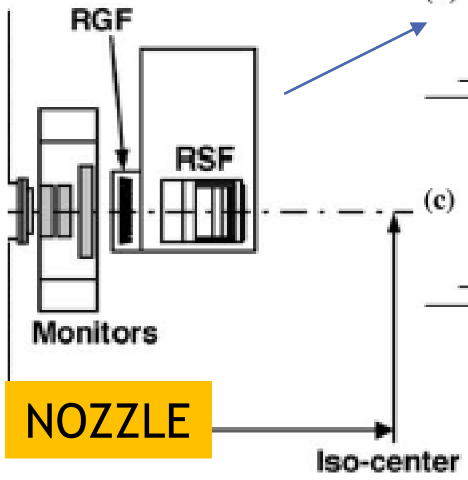


a,d Ripple filter
b,c Beam monitor
e. Range shifters

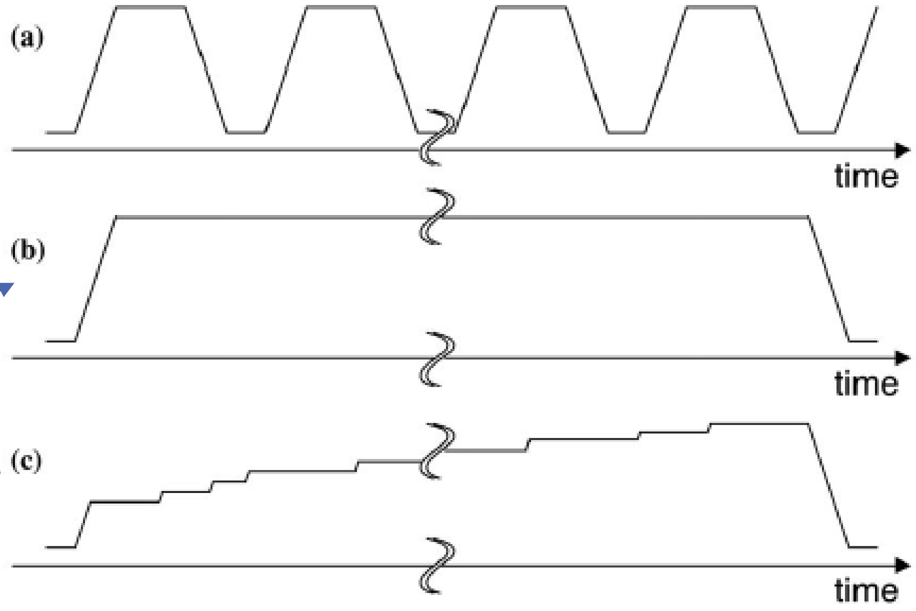
CNAO nozzle

Schematic of different HIMAC synchrotron operations

Ridge filter and range shifters



NOZZLE

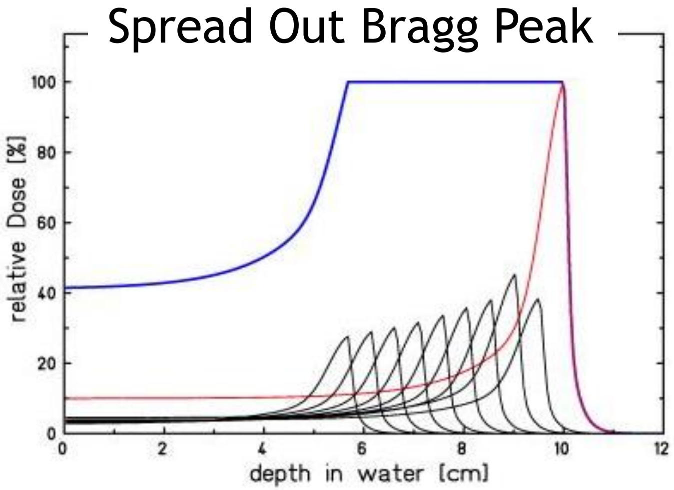


a. Conventional slow cycling synchrotron
b. Extended flattop
c. More flexible operation as alternative of RSF

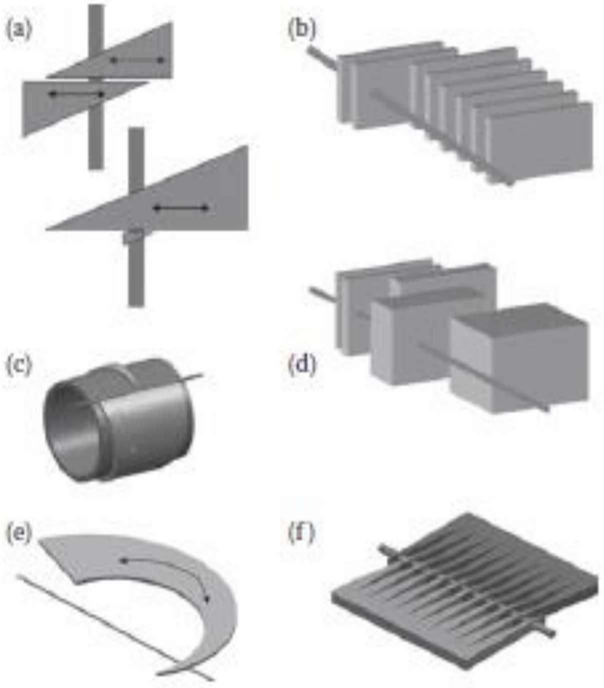
[T. Furukawa et al Med Phys 2007]

DDI with cyclotron for beam energy modulation

Several different degraders have been developed and used in the cyclotron beam transport system or for synchrotrons with only few or too high energies available.



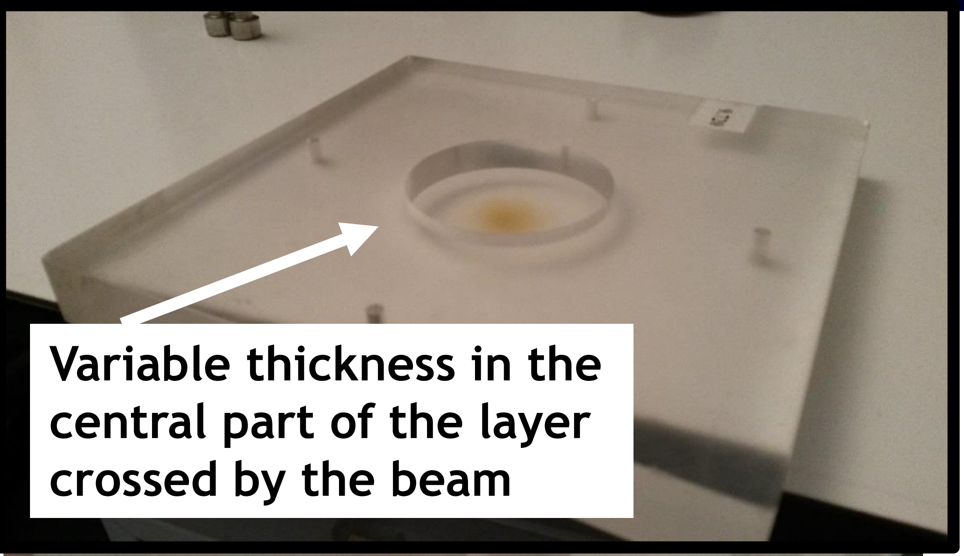
Some examples in this picture:
(a) Two or one adjustable wedges.
(b) Insertable slabs of graphite or Plexiglass.
(c) Rolled-up wedge.
(d) Insertable blocks with different thicknesses.
(e) Rotatable Plexiglass curved wedge.
(f) Adjustable multiwedge design.



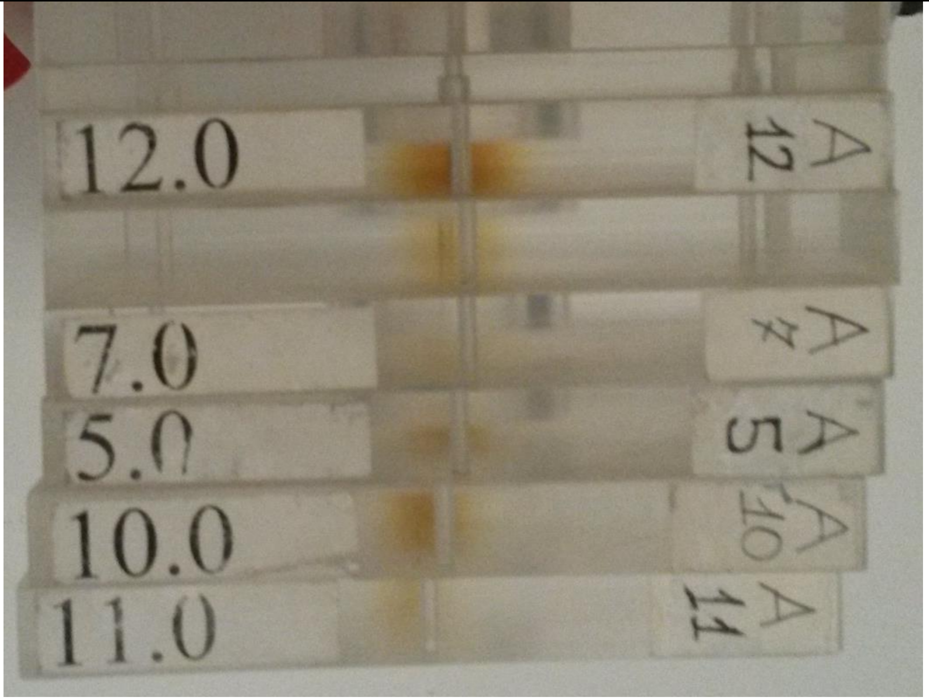
Book “Proton and carbon ion therapy”

If the degrader is fast enough it performs the energy modulation (SOBP) → PSI (5 mm step in 100 ms)

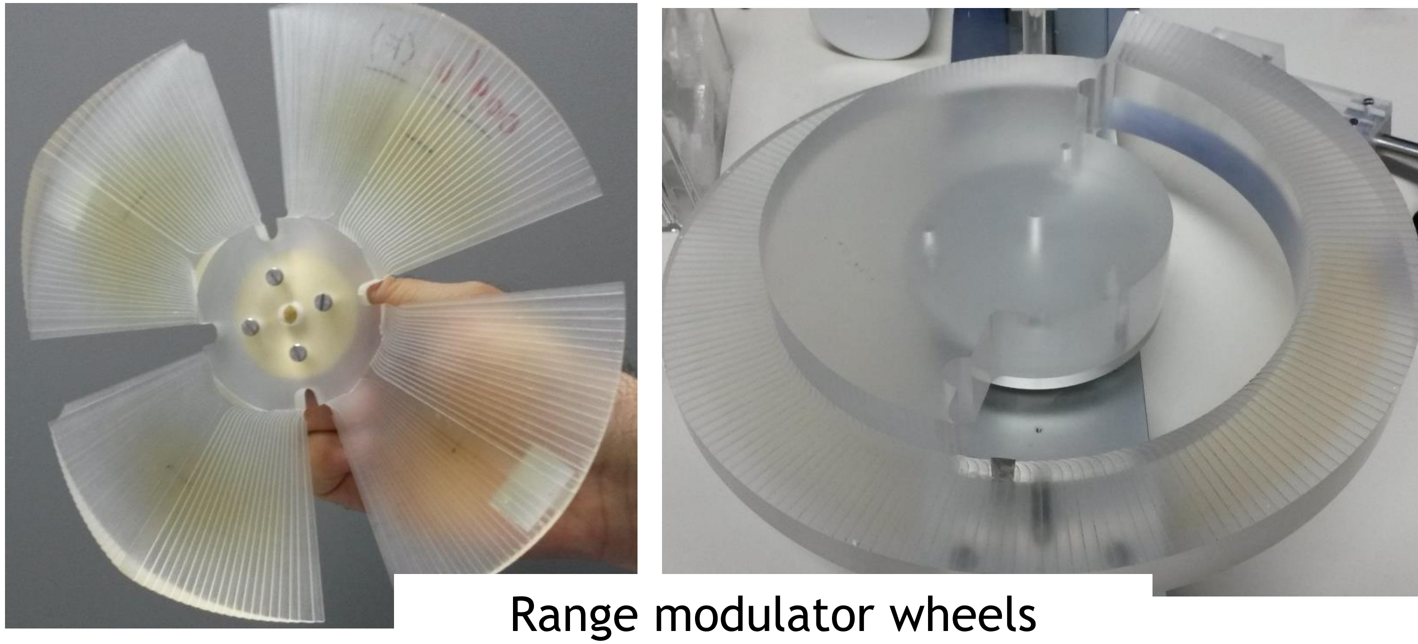
Range shifters and modulator wheels: examples



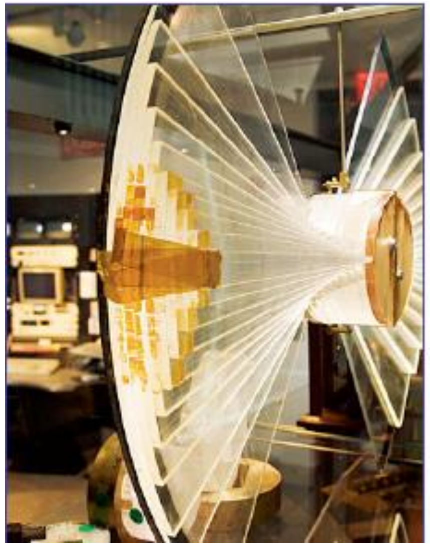
Variable thickness in the central part of the layer crossed by the beam



Fix layer dimension to use the same support



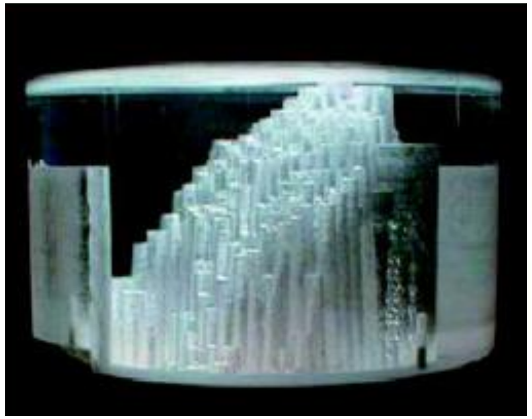
Range modulator wheels



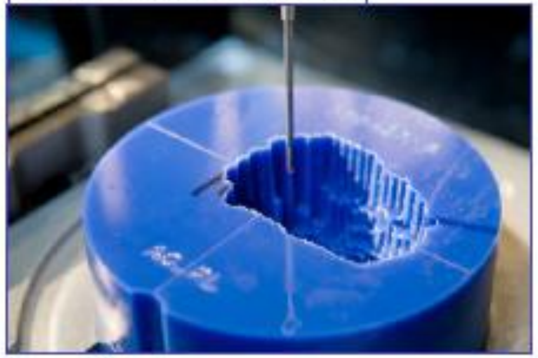
IBA design (3 tracks on single wheel, gating used to adjust modulation)

Range compensators and ridge filters

The range is modulated and compensated with materials like plexiglass, lucite, graphite, wax, …
→ Easy to shape
→ Cheaper



Wax range compensator



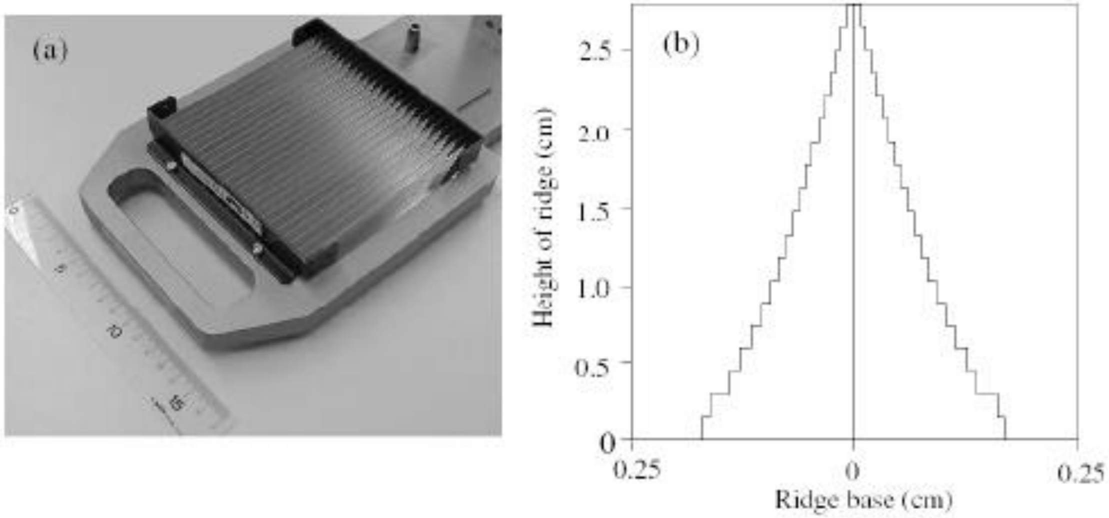
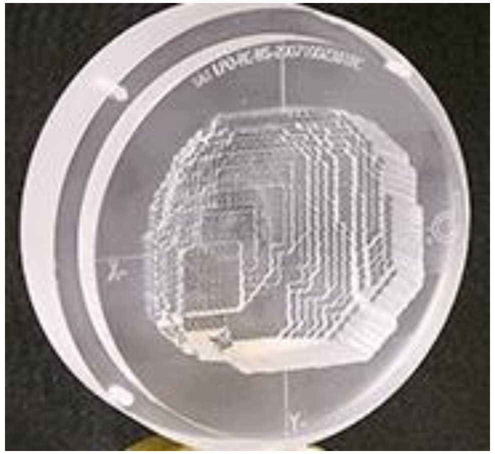
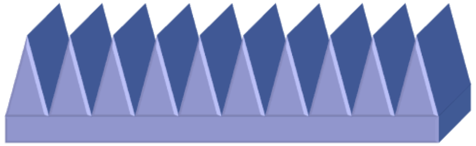


Figure 2. A bar ridge filter for the proton beam in the gantry nozzle (a), the cross-sectional shapes of the ridge for 6 cm SOBP (b).

Patient specific
Range compensator
(or bolus) to shape
the distal edge





Ridge filter design for proton therapy

PMB 48 (22) 2003 N301-N312

To increase the Bragg peak width
Placed far from the target (between scatterers)

Transverse spreading methods

- Passive Scattering (*only for proton beams*)
  - Single Scattering
  - Double Scattering

- Wobbling (beam scanning with scattered beam)

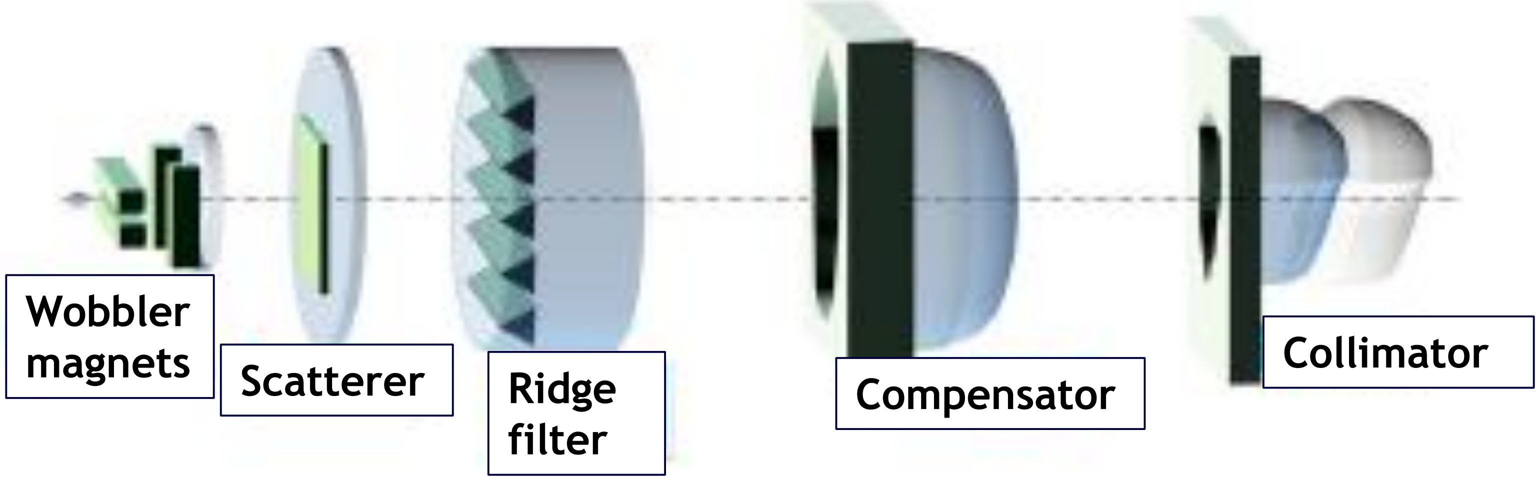
- **Only scanning with orthogonal magnets (*the most advanced method*)**

- Combined Magnetic scanning and mechanical patient movement (*only at PSI Gantry1*)

Different Dose Delivery Instrumentation

Summary (I)
Scattering with cyclotron vs Scanning with synchrotron

Scattering → Reshape the pristine beam through patient specific elements, wobbler magnets can be used in place of second scatterer



Wobbler magnets

Scatterer

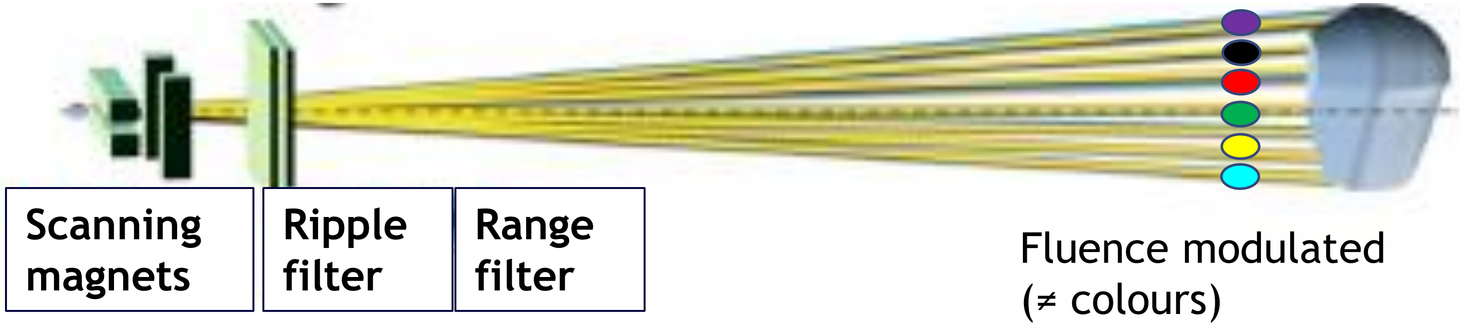
Ridge filter

Compensator

Collimator

Final collimators and compensators are *patient specific*

Scanning → Move the pristine beam through orthogonal dipoles; Dynamic energy variation



Scanning magnets

Ripple filter

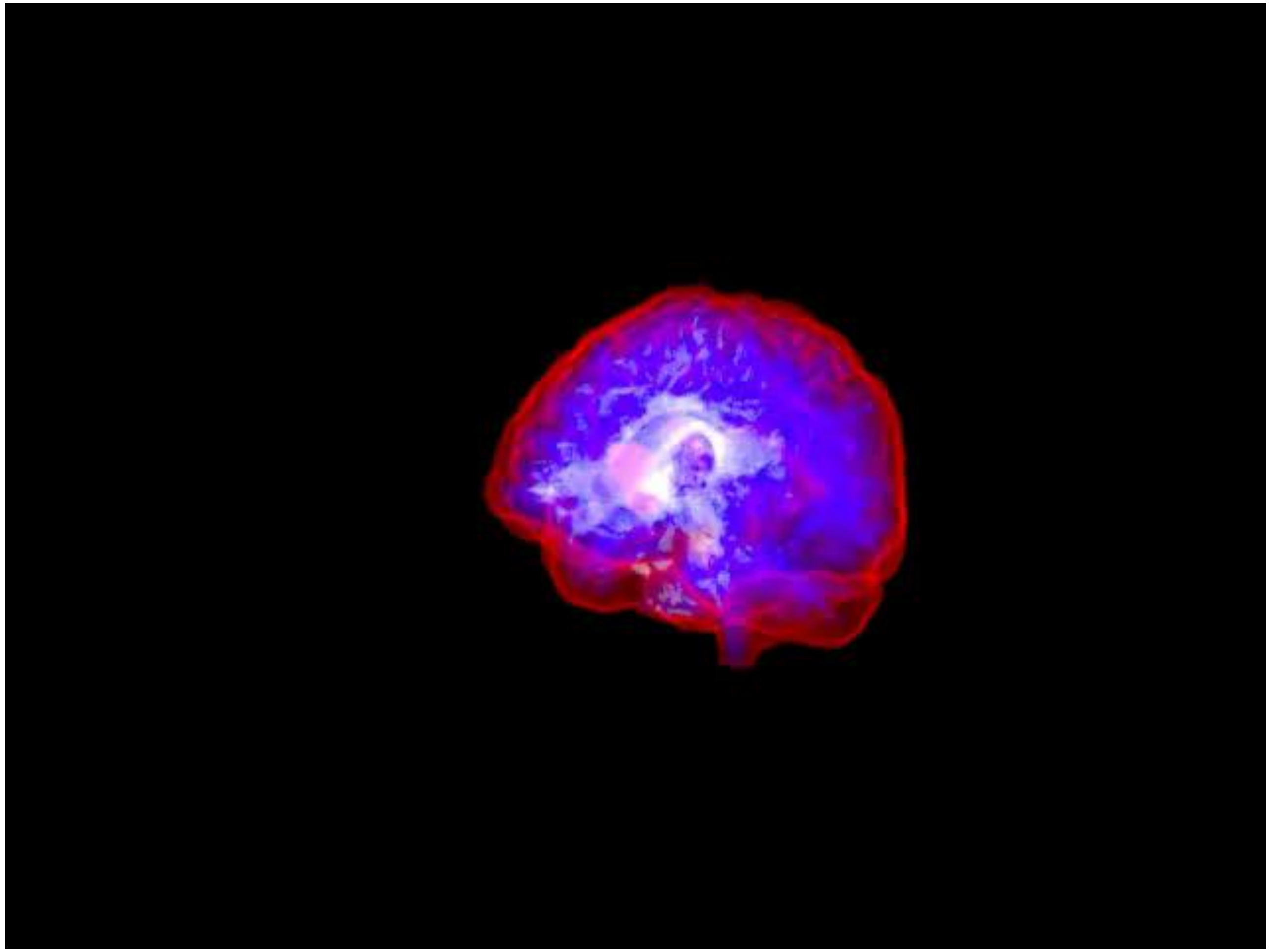
Range filter

Fluence modulated
(≠ colours)

Picture by Book
“Carbon-Ion Radiotherapy”
H-Tsujii

3D Modulated scanning ion therapy

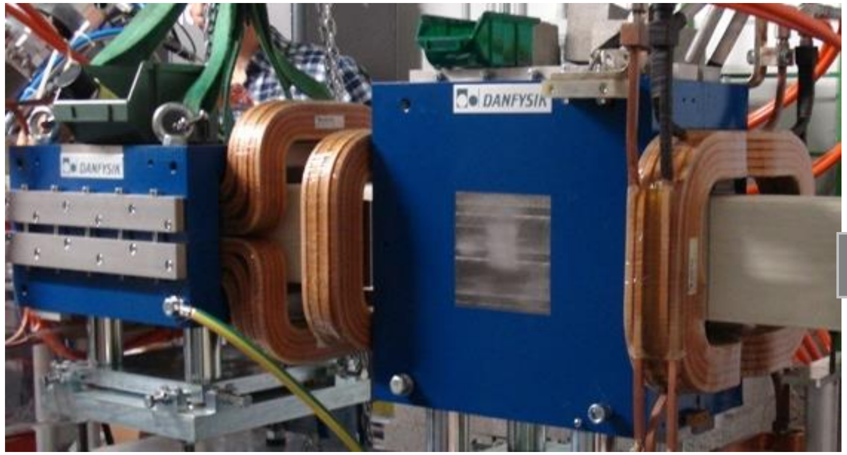
Currently one of the most advanced dose delivery technique



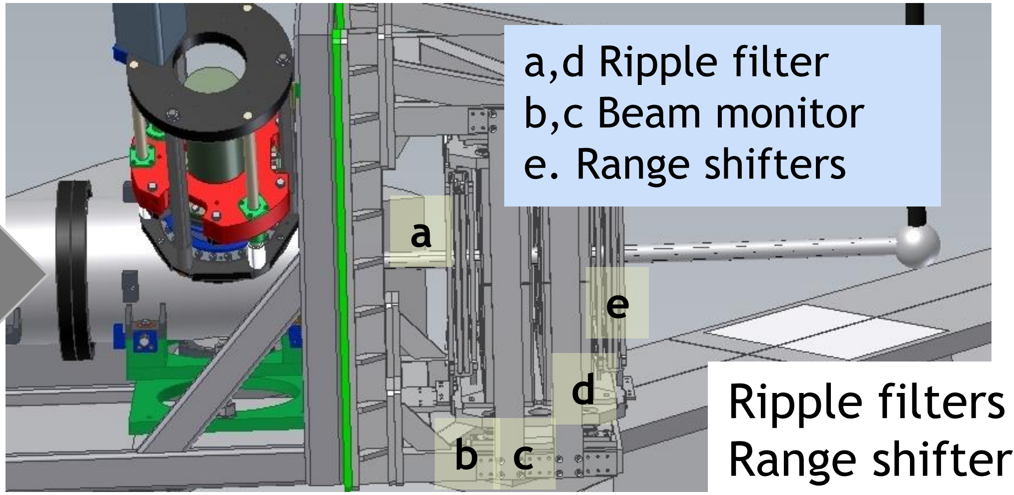
by A.Attili
INFN Torino

Scanning magnets and beam monitors: the main DDI for modulated scanning technique

Scanning magnets



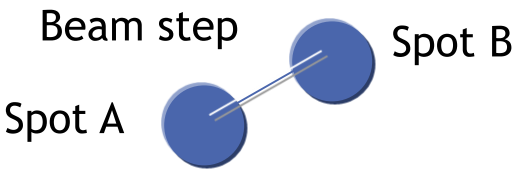
Beam monitors



a,d Ripple filter
b,c Beam monitor
e. Range shifters

Ripple filters
Range shifters

Scanning parameters: scan speed (step, time) – beam intensity – dose (spot fluence)



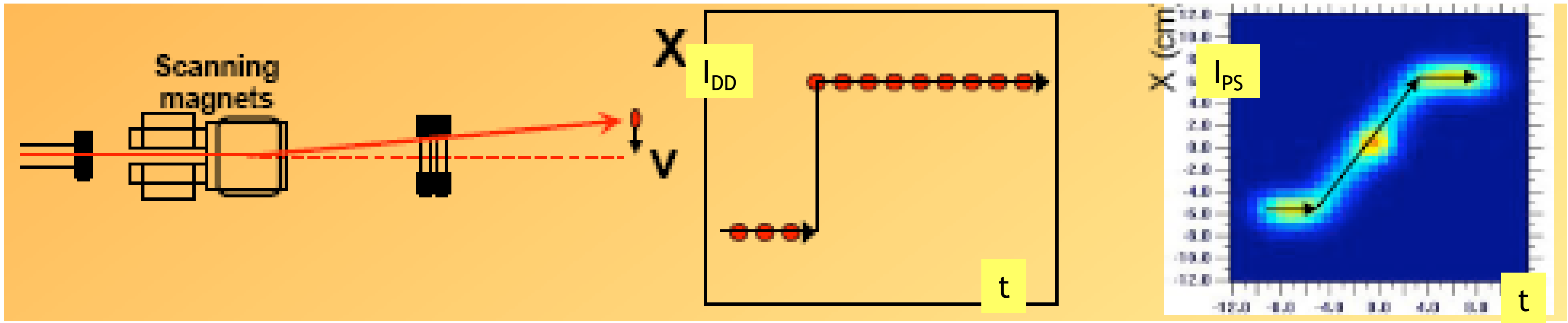
$\Delta t_{A\text{-}B}$ = time step → depends on communication delay and transient time

$\Delta I_{A\text{-}B}$ = current step (depends on $B\rho$)

$B\rho$ = 1.14 Tm (p at 60 MeV)
$B\rho$= 6.36 Tm (C^{6+} at 400 MeV/u)

Typical step = 1÷3 mm

Clinical requirement v > 20 m/s → dI/dt > 140 kA/s current ramp rate



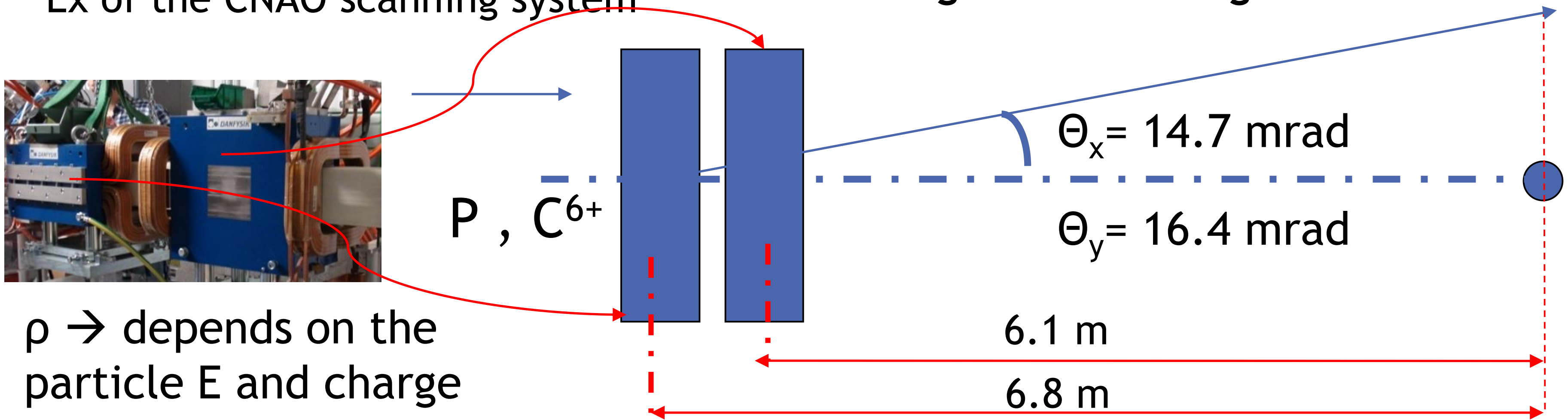
Step planned by Dose Delivery from planned coordinate

PS current Step

Beam rigidity and maximum field of irradiation characterize scanning elements

Ex of the CNAO scanning system

Beam rigidities and magnetic fields



P , C^{6+}

Θ_x= 14.7 mrad

Θ_y= 16.4 mrad

6.1 m

6.8 m

Δ x = ±100 mm
Δ y = ±100 mm

Isocenter

dI/dt

ρ → depends on the particle E and charge

B ρ = 3.3 p (GeV/c)

Max B ρ = 6.36 Tm

Values to reach a minimum scanning speed of 20 m/sec

Particles	***Energy [MeV/u]***	***(Bρ) [Tm]***	***H-lines***		
			D_x≈ 6.8 m	D_y≈ 6.1 m	di/dt
			U_x [V]	U_y [V]	[A/ms]
Protons	60	1.14	51.97	57.93	13.17
Protons	250	2.43	110.78	123.49	28.07
C-ions	120	3.26	148.62	165.67	37.65
C-ions	400	6.36	289.94	323.21	**73.46**

Maximum step and particles have to be defined to design scanning elements and beam line

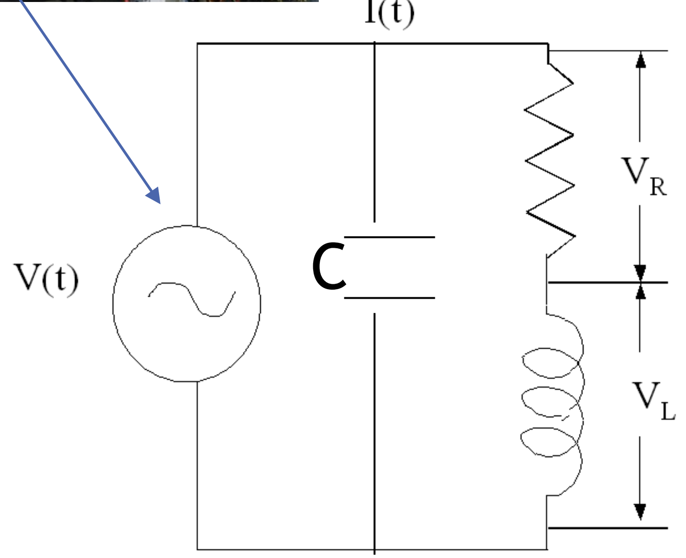
Protons ≠ Carbon ions

Δ x = ±100 mm
Δ y = ±100 mm
≠
Δ x = ±5 mm
Δ y = ±5 mm

Scanning magnet with advanced power supply

Power Supply

Dipole



Circuit R-L with R~ 50 mΩ e L~ 5 mH

$i(t) = V_C/R\,(1-\exp(-t/\tau))$ for short times → $i = (V_c/L)t$

Vc=Voltage supplied by a dedicated power supply

τ = L/R ~ 100 msec → very large time compared to ~200 us max transient time between two spots → The time constant can be shortened by three orders of magnitude with the delivering of a large voltage step aborted when the current is close to the required value.The precise adjustment is achieved via smaller voltage steps

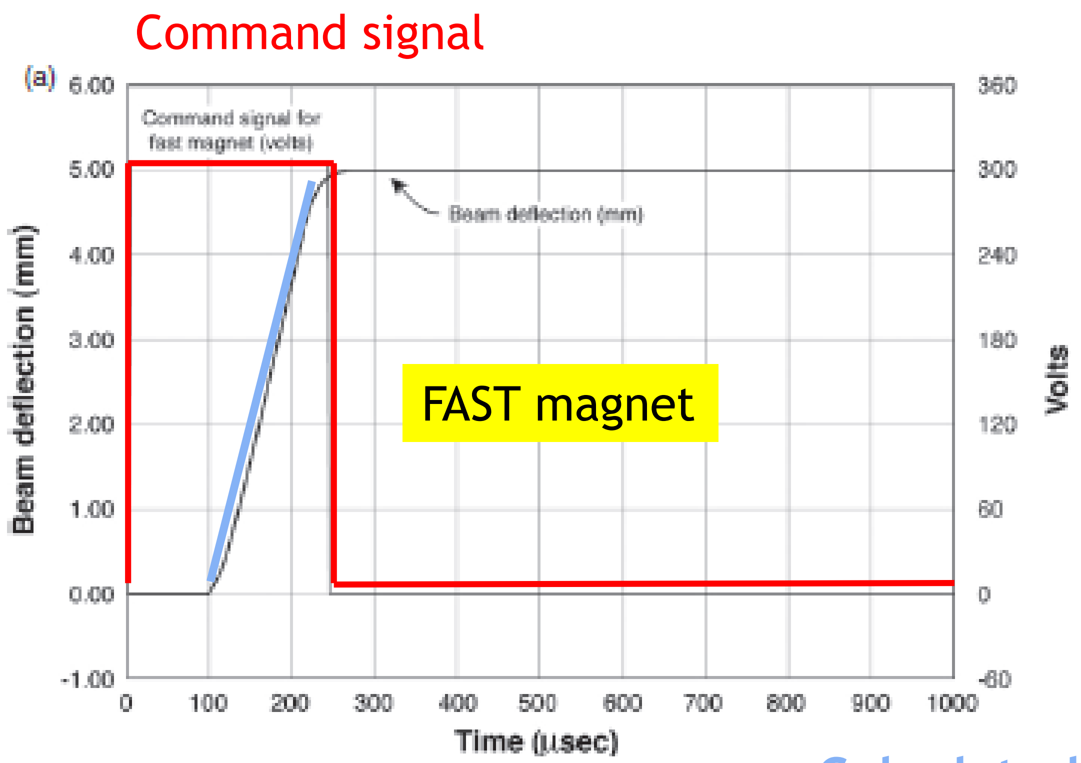
Energy required for each step

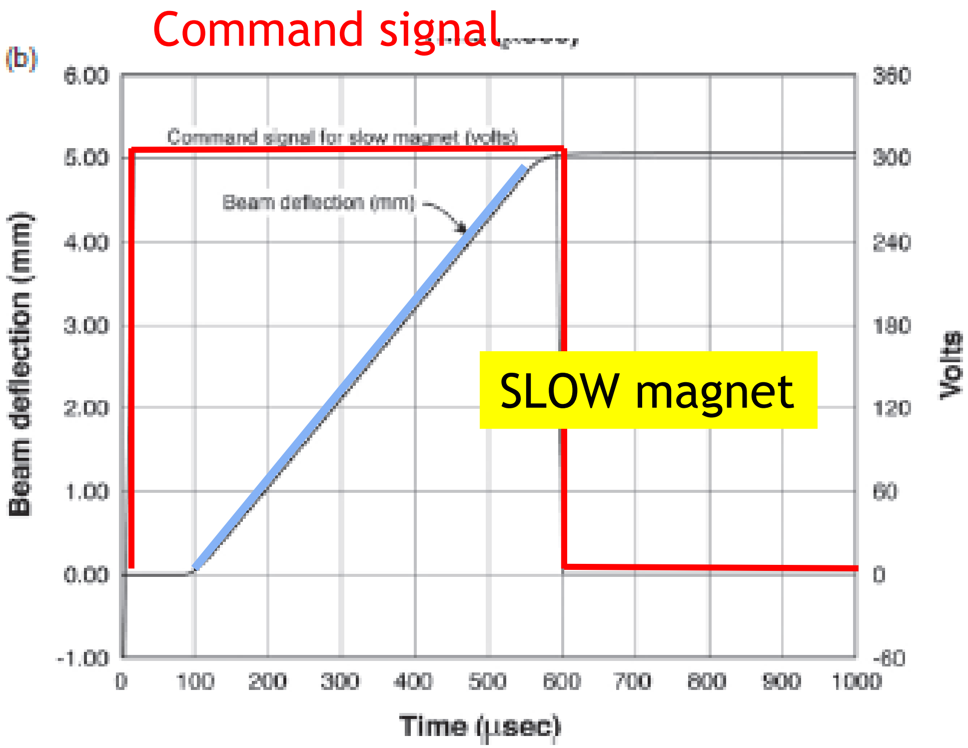
$E_L = (L\Delta I/\ \Delta t_S)\ I_S\ \Delta t_S = L\ I_S\ \Delta I$

- Δ I = current step
- I_S → Instantaneous current
- Δt_S = averaged time to provide the current step

The Power Supply is characterized by ΔI (required current step range) and Δt (maximum time accepted to provide the current without ripple).
Critical steps have to be considered (heavier ions at maximum Energy).

Fast and slow magnets response for 5 mm step command





Calculated magnet response

G Coutrakon et al "Dose error analysis for a scanned proton beam delivery system" Phys. Med. Biol. **55** (2010) 7081–7096

Beam monitors

Overall task of the dose delivery beam monitors

To measure before the patient …

Number of particles (beam Intensity – dose rate)
→ *Accepted uncertainty 1-2 %*

Transversal Beam positions (c.o.g)
→ *Accepted uncertainty 0.5 mm*
Transversal Beam shape (FWHMs - symmetry)
→ *Accepted uncertainty 1 mm*

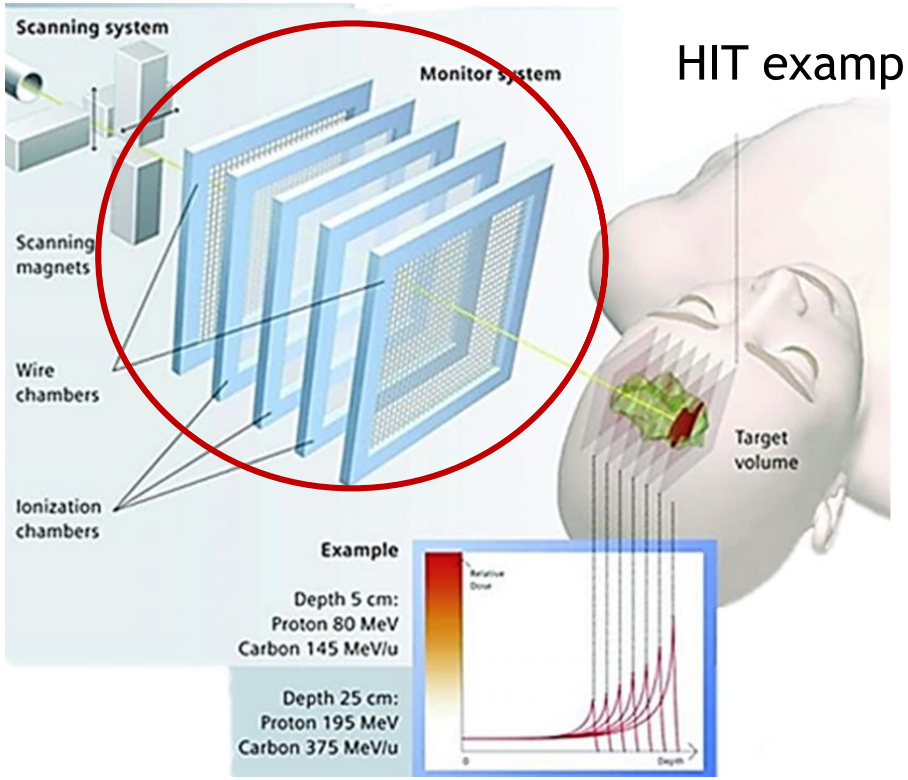
Mean beam energy
→ *Accepted uncertainty 1-2 %*

Beam Monitors for Scanning and Scattering systems

FOR ALL THE SYSTEMS AND ADELIVERY TECHNIQUES beam monitors are mandatory for On-line check of the beam parameters before the patient. Real-Time operations are required to react to any condition leading to a potential hazard

Additional requirements ONLY for Scanning System:

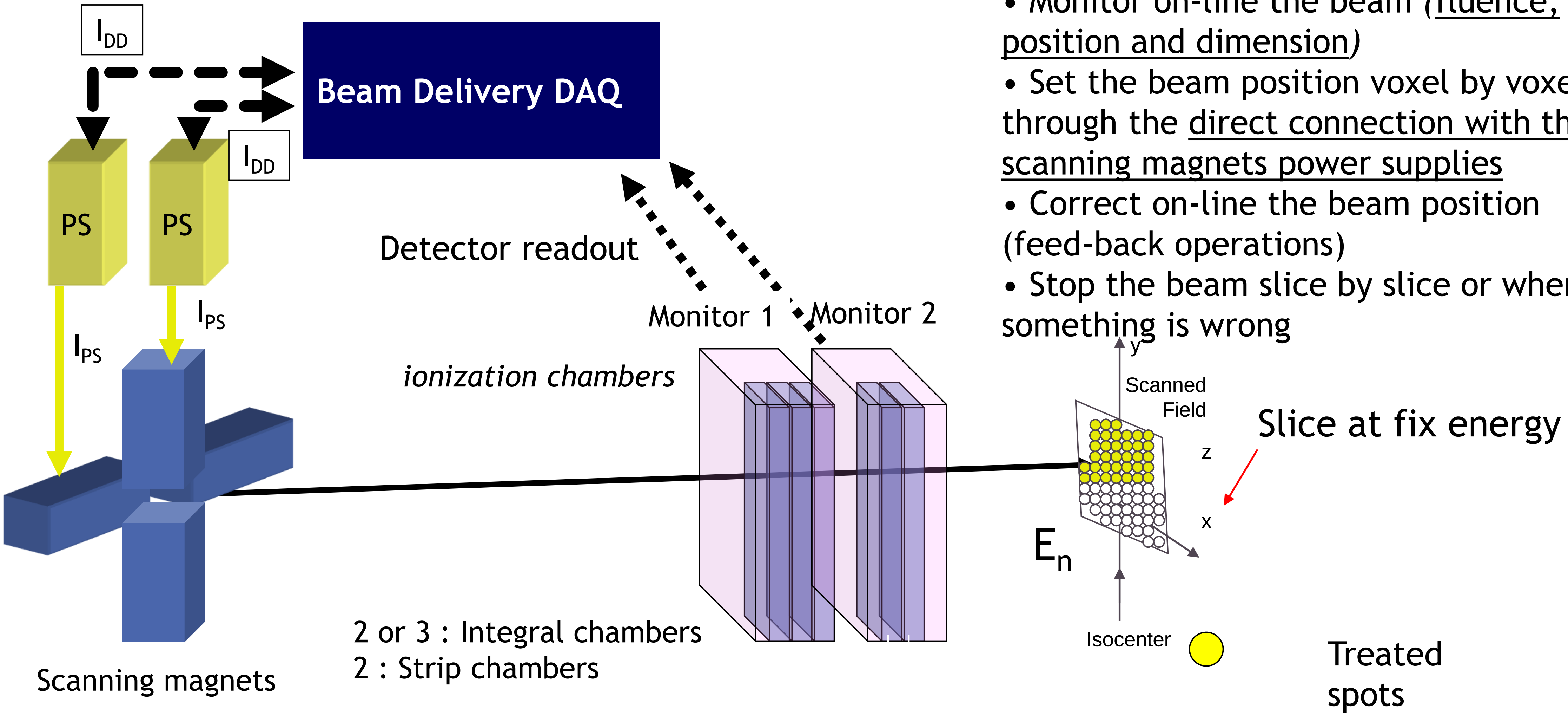
- **Drive the delivery progress**
- **Depend on delivery time structure**
- Perform RT **feedback on beam characteristics (mainly acting on scanning magnets to correct small beam position deviations)**



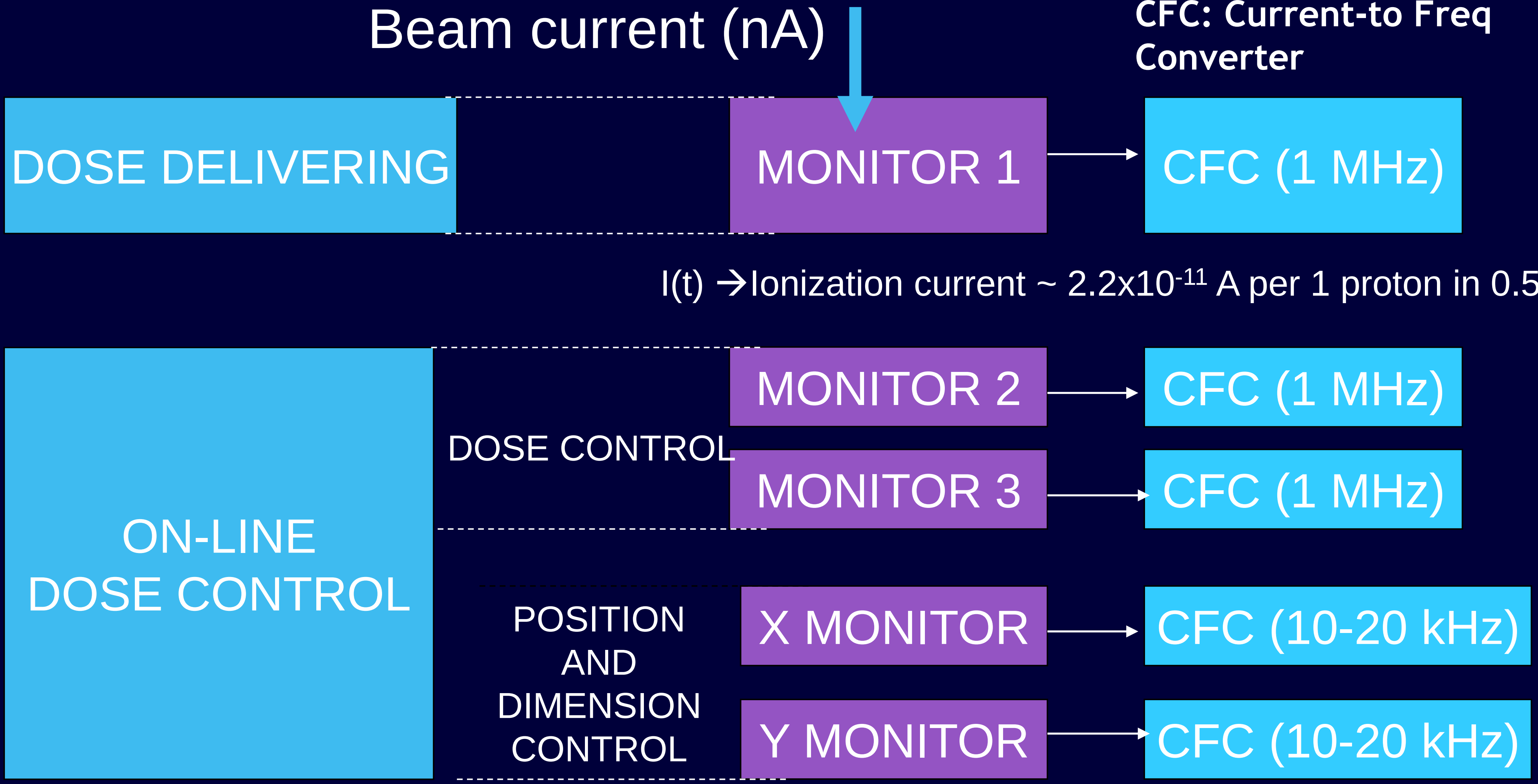
HIT example

For modulated scanning technique the beam monitors are used to drive the treatment

- Monitor on-line the beam (fluence, position and dimension)
- Set the beam position voxel by voxel through the direct connection with the scanning magnets power supplies
- Correct on-line the beam position (feed-back operations)
- Stop the beam slice by slice or when something is wrong



Required Monitor sequence



Beam current (nA)

CFC: Current-to Freq Converter

DOSE DELIVERING

MONITOR 1 → CFC (1 MHz)

I(t) →Ionization current ~ 2.2×10^{-11} A per 1 proton in 0.5 cm of N_2

ON-LINE DOSE CONTROL

DOSE CONTROL

MONITOR 2 → CFC (1 MHz)

MONITOR 3 → CFC (1 MHz)

POSITION AND DIMENSION CONTROL

X MONITOR → CFC (10-20 kHz)

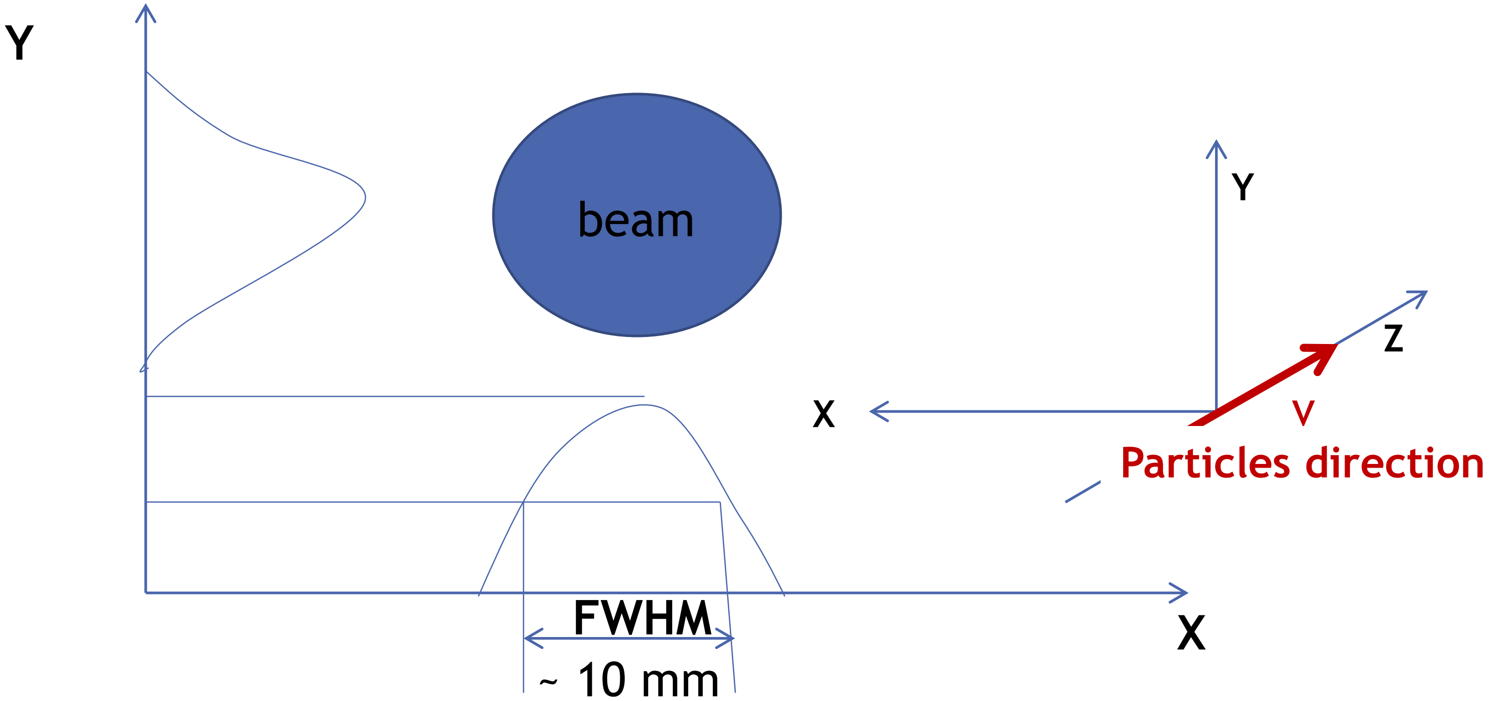
Y MONITOR → CFC (10-20 kHz)

Some numbers on beams we have to measure

- *Proton* (charge +1, m_p 0.93827 GeV/c^2 = 1.673 x 10^{-27} kg)
- Carbon ion, Z = 6, totally ionized : charge +6

~ 10^9 particles/sec → 1 part/nsec

1 nsec : <t> between 2 particles



Beam energy and particle speed

$$E = E_K + m_p = \sqrt{p^2 + m_p^2}$$

$$\beta = \frac{v}{c} = \frac{p}{E} \qquad p = \sqrt{E^2 - m^2}$$

$$\beta = \frac{\sqrt{1 + 2\frac{m_p}{E_K}}}{1 + \frac{m_p}{E_K}} \cong \mathbf{0.65} \rightarrow \gamma = 1.32$$

for E_K ~ 300 MeV/u

β = 0.65 → **v = 0.65 * c = 200000 km/s**

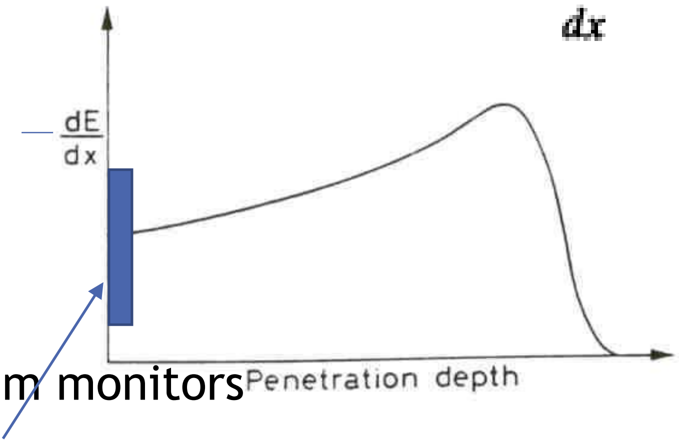
2×10^8 m/sec * 1 nsec = 0.2 m →

20 cm = <d> between 2 particles

Gas ionization by particles which cross the detector

Stopping Power

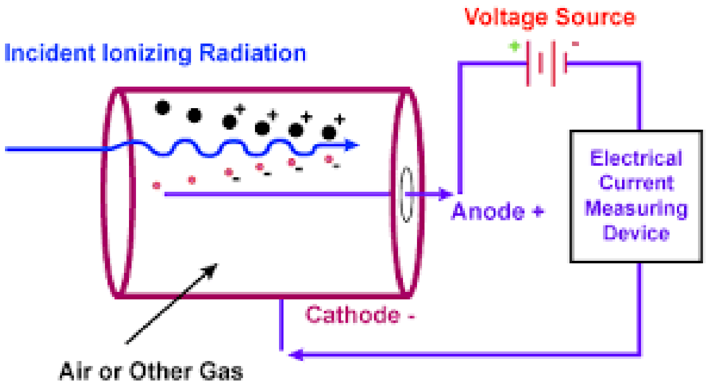
$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} NB$$



Beam monitors

ΔE is the Energy loss per particle in the chamber gap h

$$\boxed{\Delta E = h \times \frac{\mathrm{d}E}{\mathrm{d}x}(E, \mathrm{particle}, \mathrm{medium})}$$



$$N = \frac{\Delta E}{W}$$

N° of charges e-/ion created by ΔE lost

W depends on gas properties

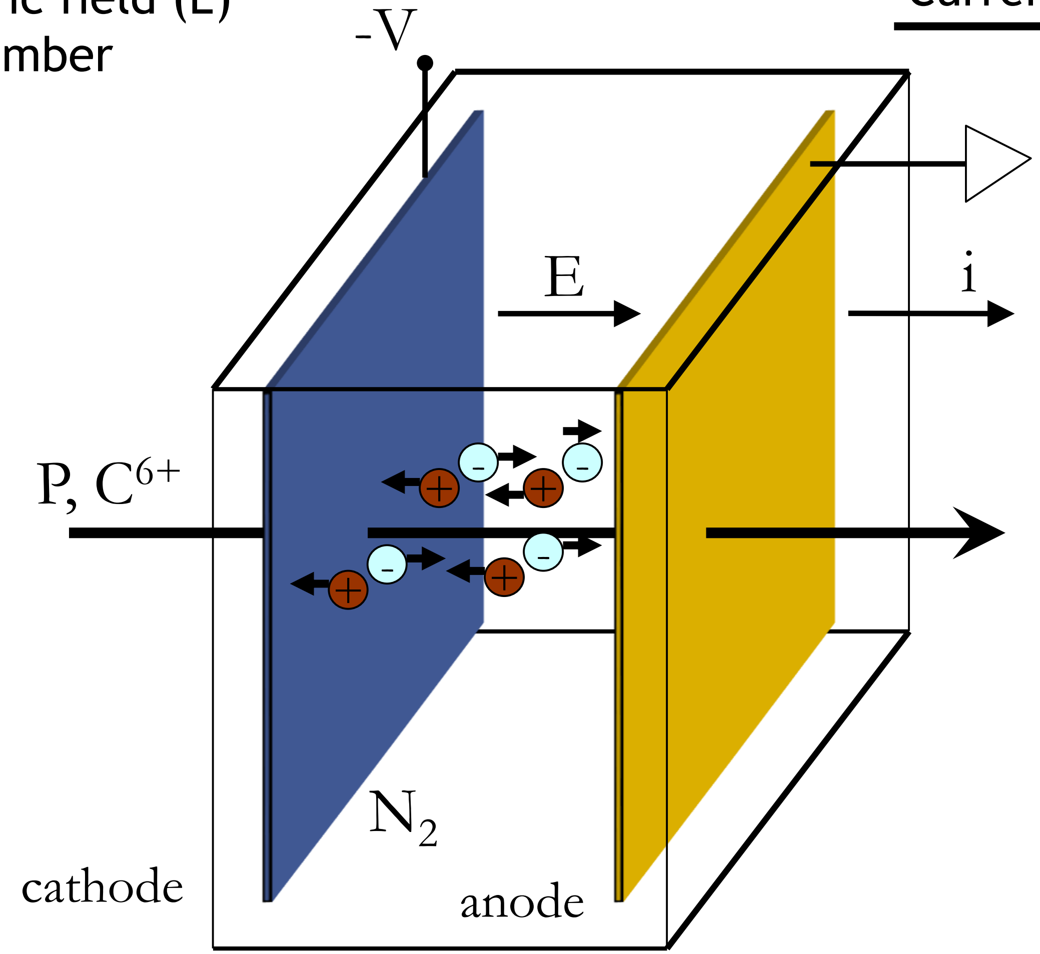
- Density
- Atomic Number
- Mass number

$$Q = e\frac{\Delta E}{W}$$

Collected charge at the detector electrodes (without recombination effects)

Parallel plate ionization chambers

Uniform electric field (E) within the chamber



Current →

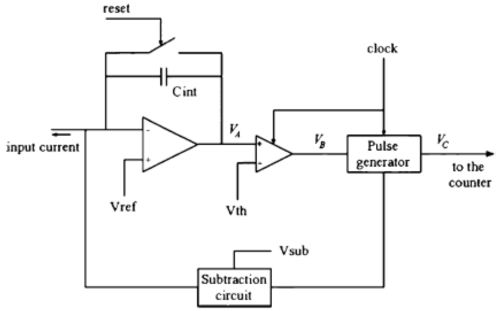


Fig. 1. Current-to-frequency converter scheme [8].

Counts →

$$\text{Counts} \propto Q \propto D \times \varrho(p, T)$$

$$Q = \frac{D\rho V}{W}$$

$D = Dose \quad \Delta E / m \, (Gy)$

$\rho = gas \quad density \, (Kg/m^3)$

$V = volume \, (m^3)$

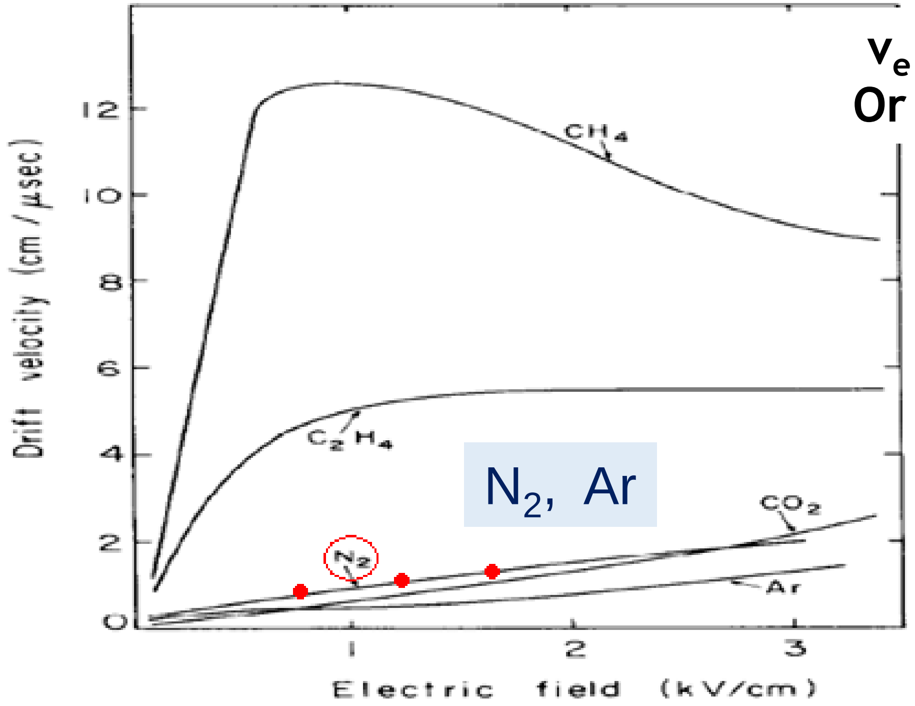
$W = Ionization \quad Potential \, (eV)$

Electrons and ions drift velocity (particle mobility)

$$v = \mu E$$

Electrons

E = 1000 V/cm
Pressure 760 mmHg



N_2, Ar

v_e = 1 cm/μsec
Or 10 μm/ns

500 nsec to cross 5 mm gap

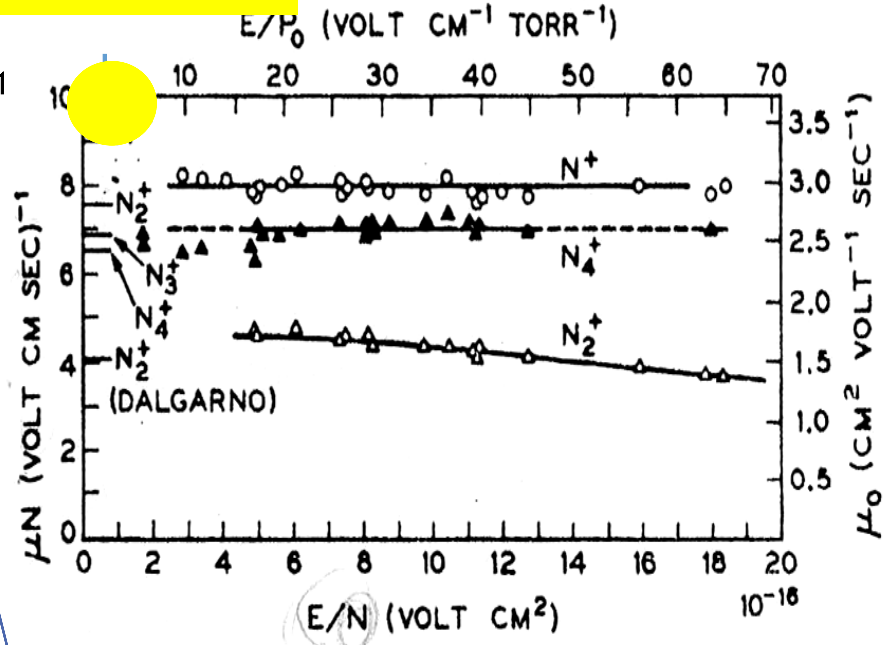
Ve- >> Vions

Ions 300 times slower

Ions

$E/p_0 \cong 1.25$ V cm^{-1} $Torr^{-1}$

μ+ ~ 3 cm^2 V^{-1} sec^{-1}

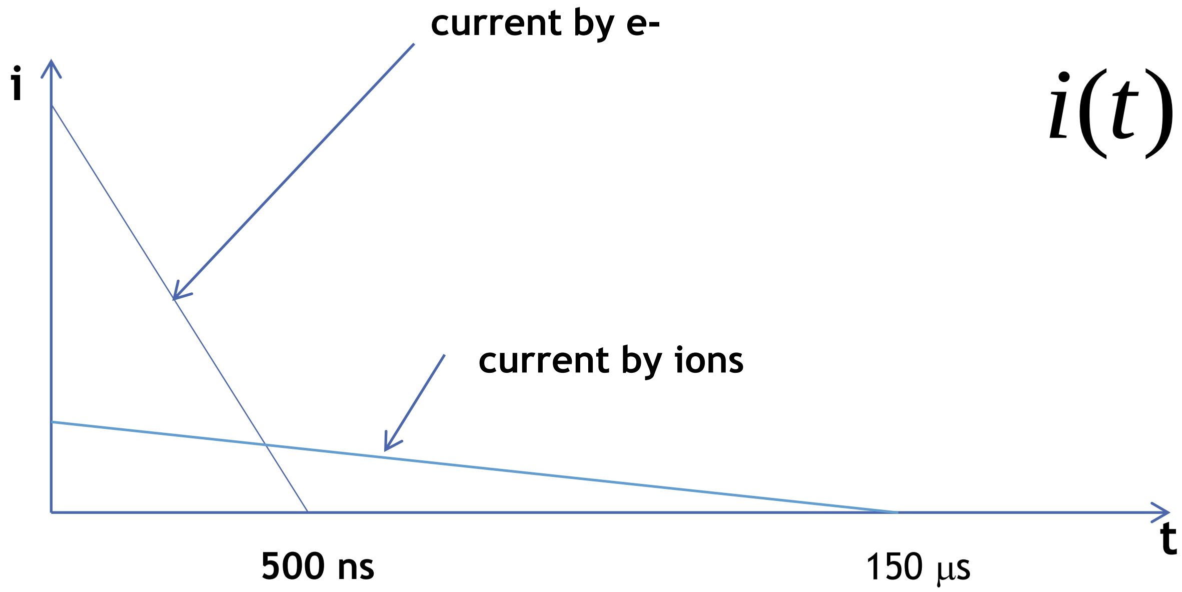


150 μsec to cross 5 mm gap

v = 3 cm^2 V^{-1} sec^{-1} * 1000 V cm^{-1} =
3000 cm/sec = 1 cm/300 μsec

Current collected with ionization chambers

Current from 1 particle that crosses 1 cm gap of N_2 or Ar



$$i(t) = -qv(t)E_m$$

The measured current is the sum of these two curves

Time/freq for data acquisition

For continuous beam the low velocity of ions affects only the first measurement and the readout frequency has to be ≈ 1 MHz

$$T = t + t'$$

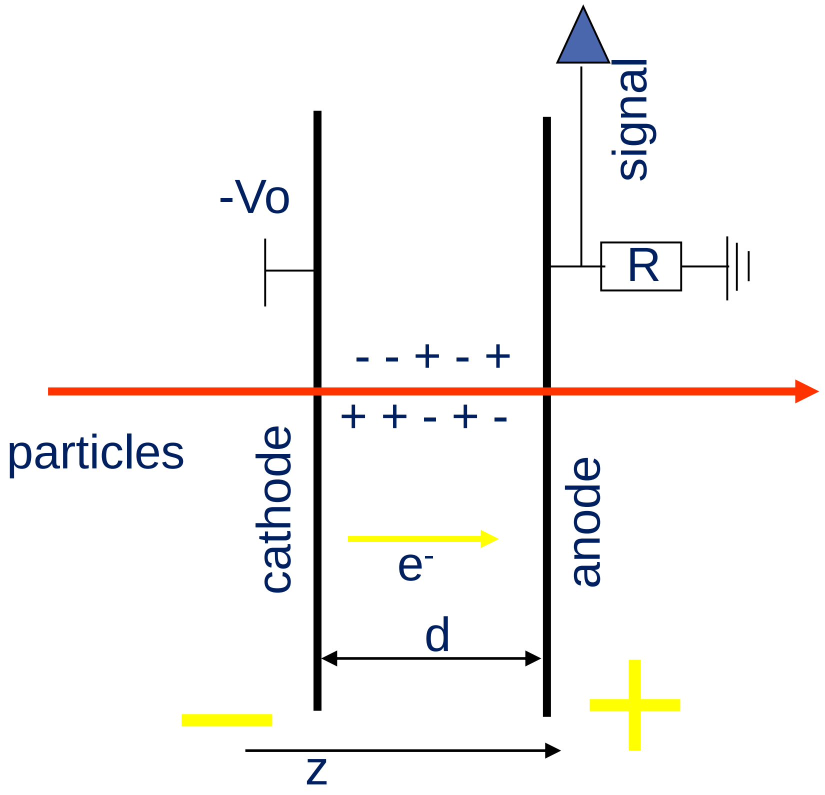
$t < 1$ μs

$v < 1$ cm/μs

N_2, Ar

t = electron drift time

t' = time to collect the charge and convert into digital signal



For d ≈ 1 cm

E ≈ 1000 V/cm

Ion-recombination in ionization measurements

- **Initial recombination**:

Recombination within one created ion cluster. Depends on material, temperature and bias voltage, not dose rate.

- **Columnar recombination**:

Recombination within one particle track. Depends on ionization density of the radiation and bias voltage, not dose rate.

- **General recombination**:

Recombination when ions interact in different particle tracks. Depends on bias voltage and dose rate.

$$\Delta Q = \Delta n * Q = \Delta n * e * N$$

$N = \frac{\Delta E}{W}$ e- /ion pair

Δn Number of particles of the beam

$$I = \frac{dQ}{dt} = e * N * \frac{dn}{dt}$$

With recombination $N_{measured} << N$

Collection efficiency: Boag’s Theory for constant dose-rate and low intensity beams

The irradiation duration has to be long compared to the ion-transit time of ~1 ms

Collection efficiency f :

$$f = \frac{1}{1+\frac{1}{6}\xi^2} \Rightarrow \xi = \sqrt{\frac{\alpha}{e\kappa_1\kappa_2}}\,\frac{\sqrt{n_0 d^2}}{V}$$

$$\mathrm{n}_0\left[{}^{\mathrm{ions}}/_{\mathrm{cm}^3}\right] = \frac{\mathrm{Q}}{e \cdot volume} \qquad \xi \rightarrow \frac{1}{V}$$

d = plate separation (cm),

n_0 = Q/vt (esu/cm^3 s) ionization density,

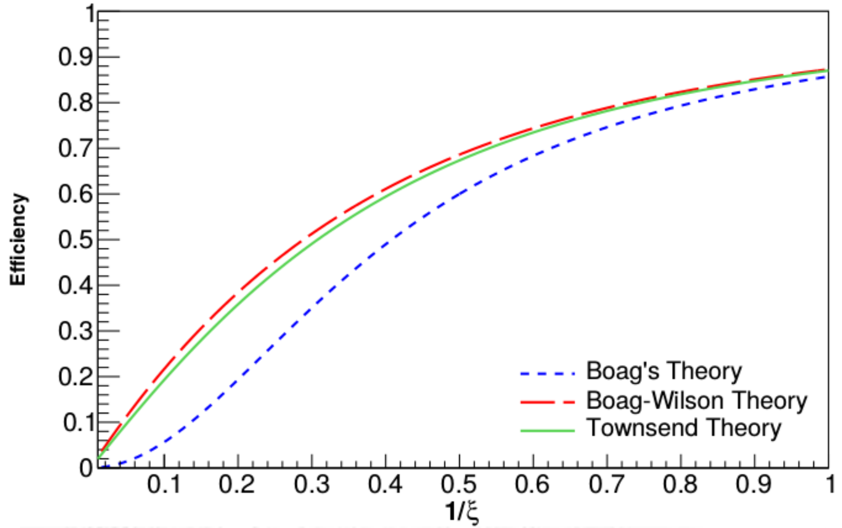
V = applied potential (V),

α = recombination coefficient (cm^3/s),

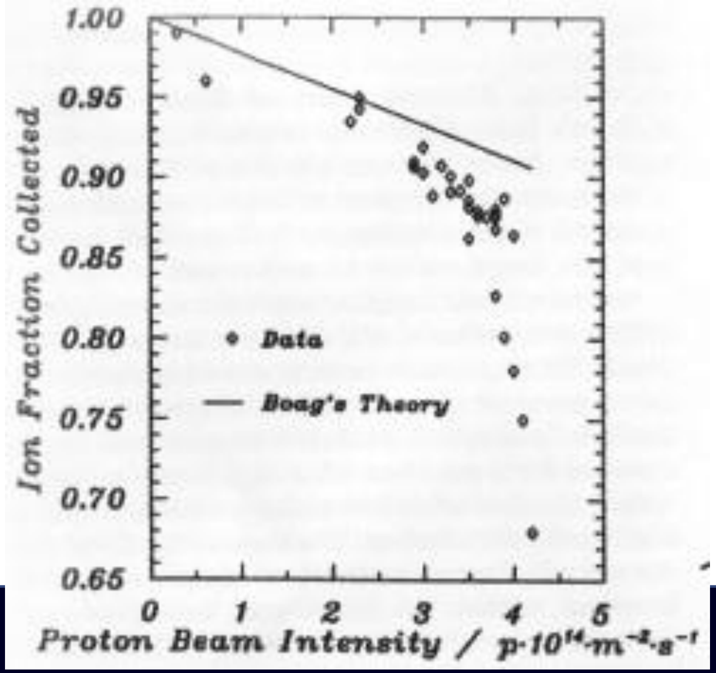
e = electron charge = 4.8032 ´ 10^{-10} esu,

k_1 = mobility of positive ions (cm^2/Vs),

k_2 = mobility of negative ions (cm^2/Vs),

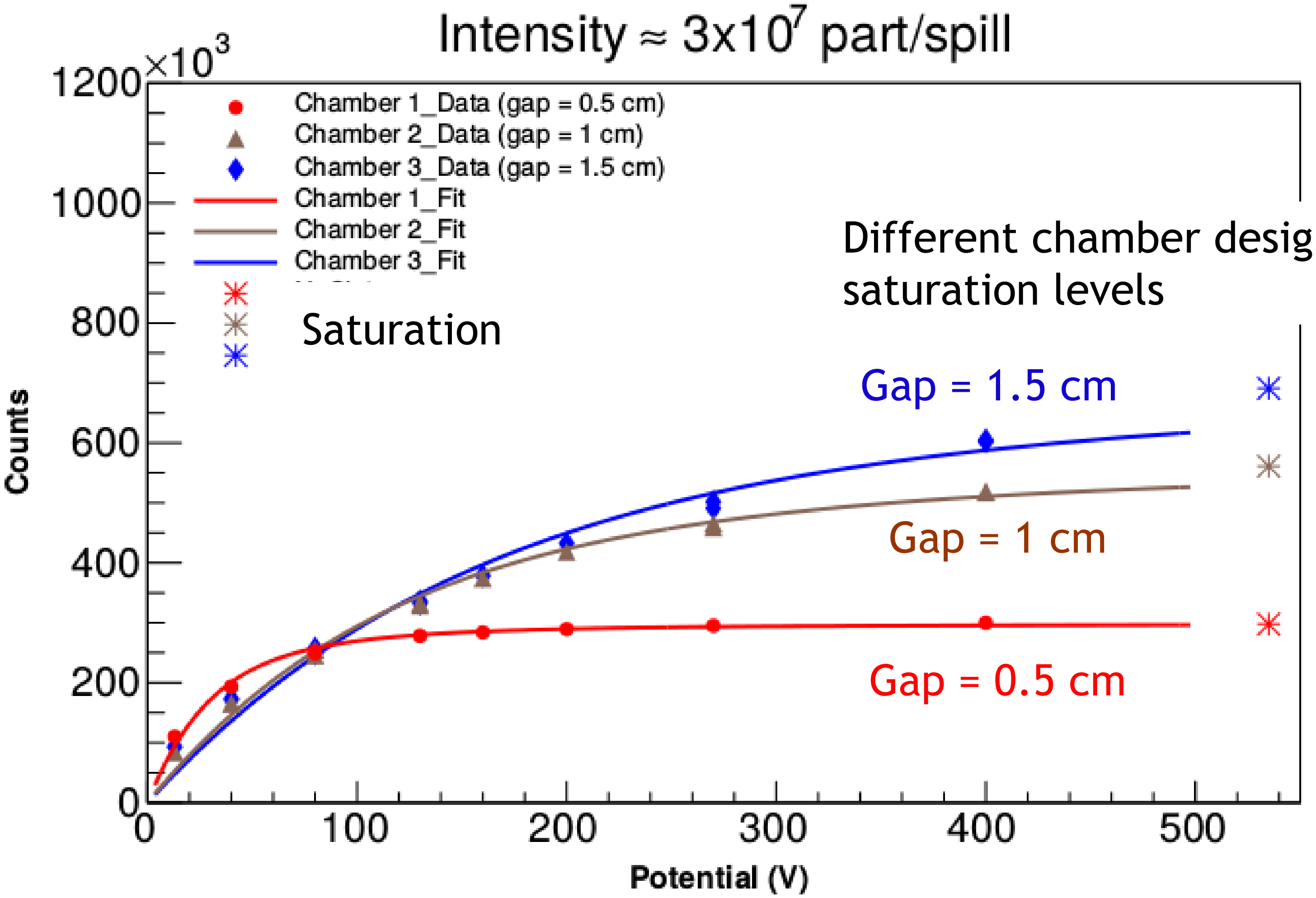


V/d^2



Gap – Gas – HV → to work in saturation region

Carbon ions
Gas: air



Saturation

Different chamber design → different saturation levels

Gap = 1.5 cm

Gap = 1 cm

Gap = 0.5 cm

Transmission parallel plate ionization chambers

Thin electrodes “transparent” to the beam

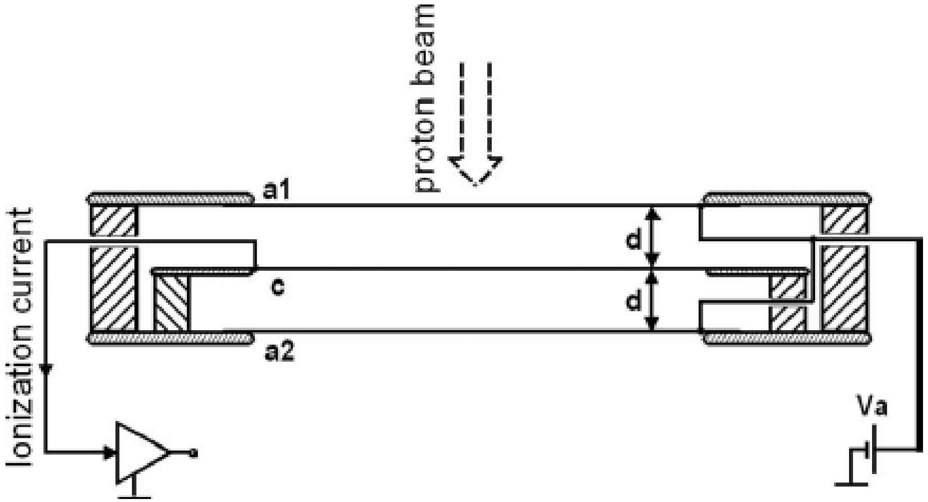
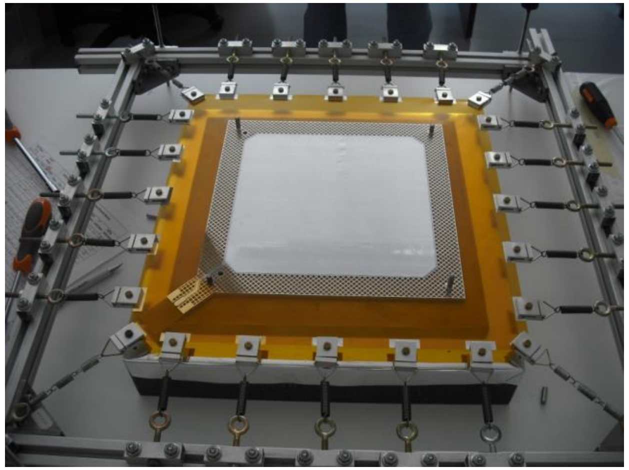


FIG. 5. Schematic representation of the parallel-plane ionization chamber (monitors 1 and 2). V_a (2000 V) is the applied voltage to the anodes (a1 and a2), and d is the spacing between the anode and the cathode (c). Monitor 1 has d=0.5 cm and monitor 2 has d=1 cm.

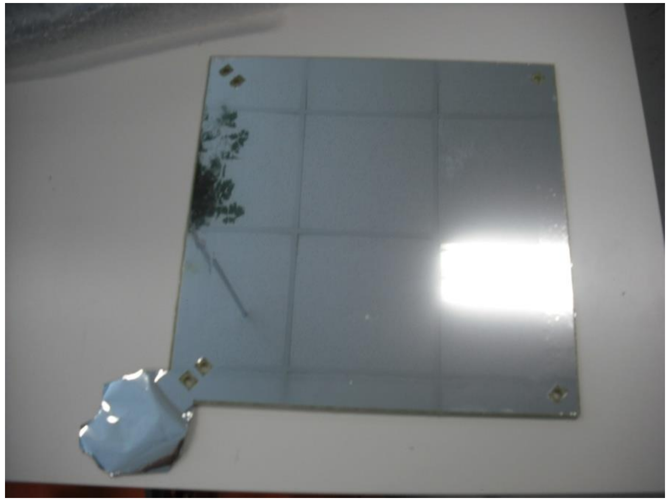
PSI : chamber filled with air → HV = 2000 V (d=0.5 cm and d=1 cm)

CNAO: chamber filled with N_2 → HV = 400 V
d = 0.5 cm

Anode



Cathode



Beam monitors to measure position and width: ionization chambers with segmented anodes

Time resolution

1 µs → 100 µs → 200 µs

No segment STRIP PIXEL

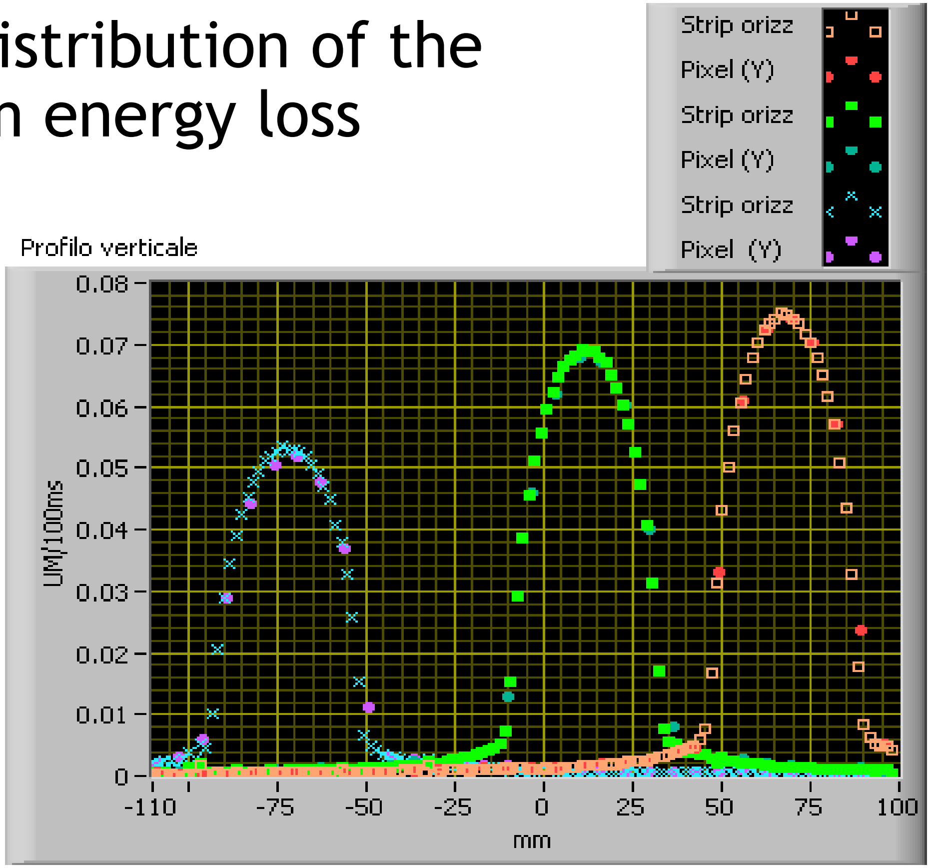
Example of anodes
For 24x24 cm^2
sensitive area

Resolution for Beam Position measurements

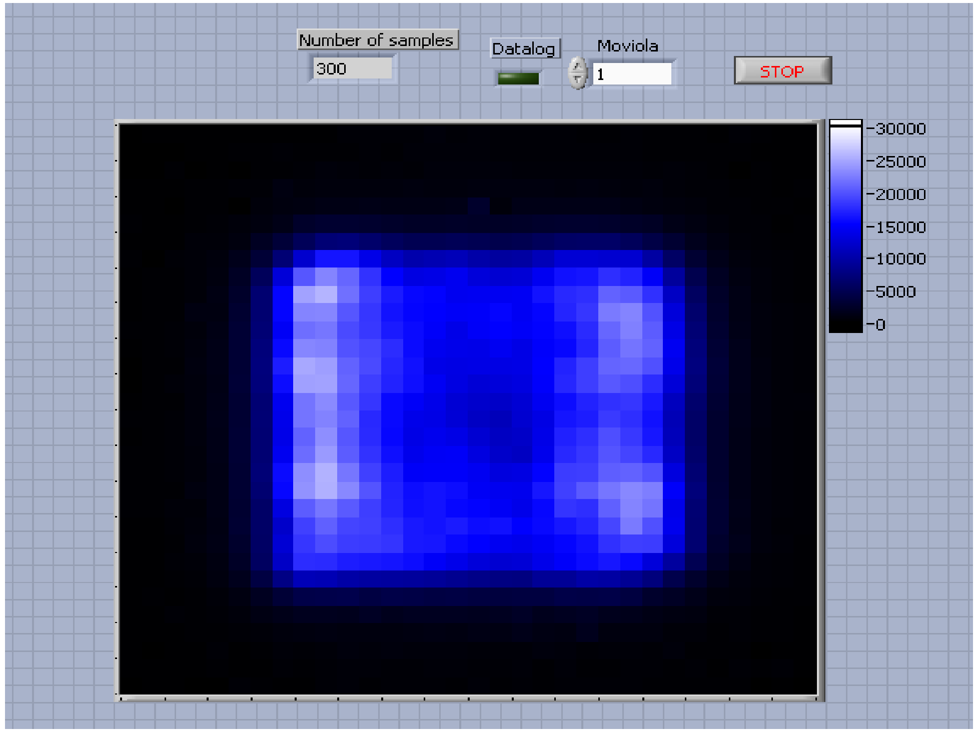
--------------- → 100 µm → 200 µm

Strips vs pixels

- 1D distribution of the beam energy loss



- 2D distribution of the beam energy loss


Number of samples 300

Moviola 1

Pitch strip = 1,5 : 2 mm

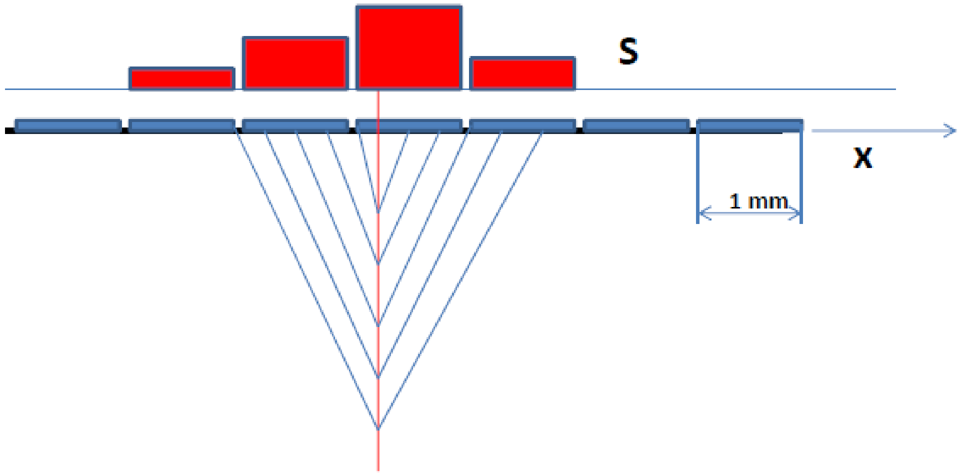
Pitch pixel = 5,5 : 7.5 mm

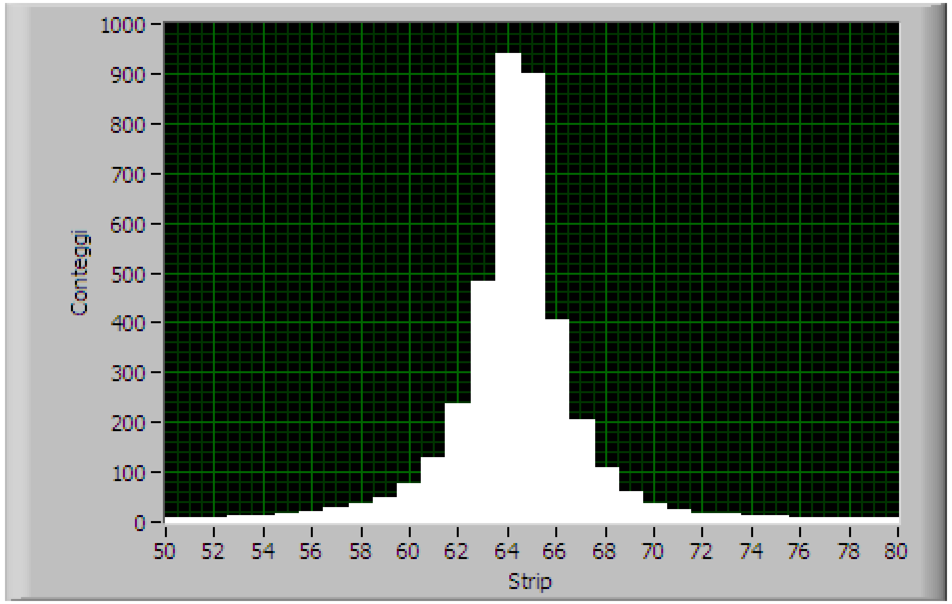
Beam Position Resolution = 100 µm

Beam Position Resolution = 200-300 µm

Beam position measured using the center of gravity

Parallel plate ionization chambers with segmented anodes





$$x = \frac{\sum x_i^{strip} * S_i}{\sum S_i}$$

$$S'_i = \begin{cases} S_i & \text{if } S_i \neq 1; \\ 0 & \text{if } S_i = 1. \end{cases}$$

Set at 0 strip with very low counts

Position accuracy depends on number of readout counts

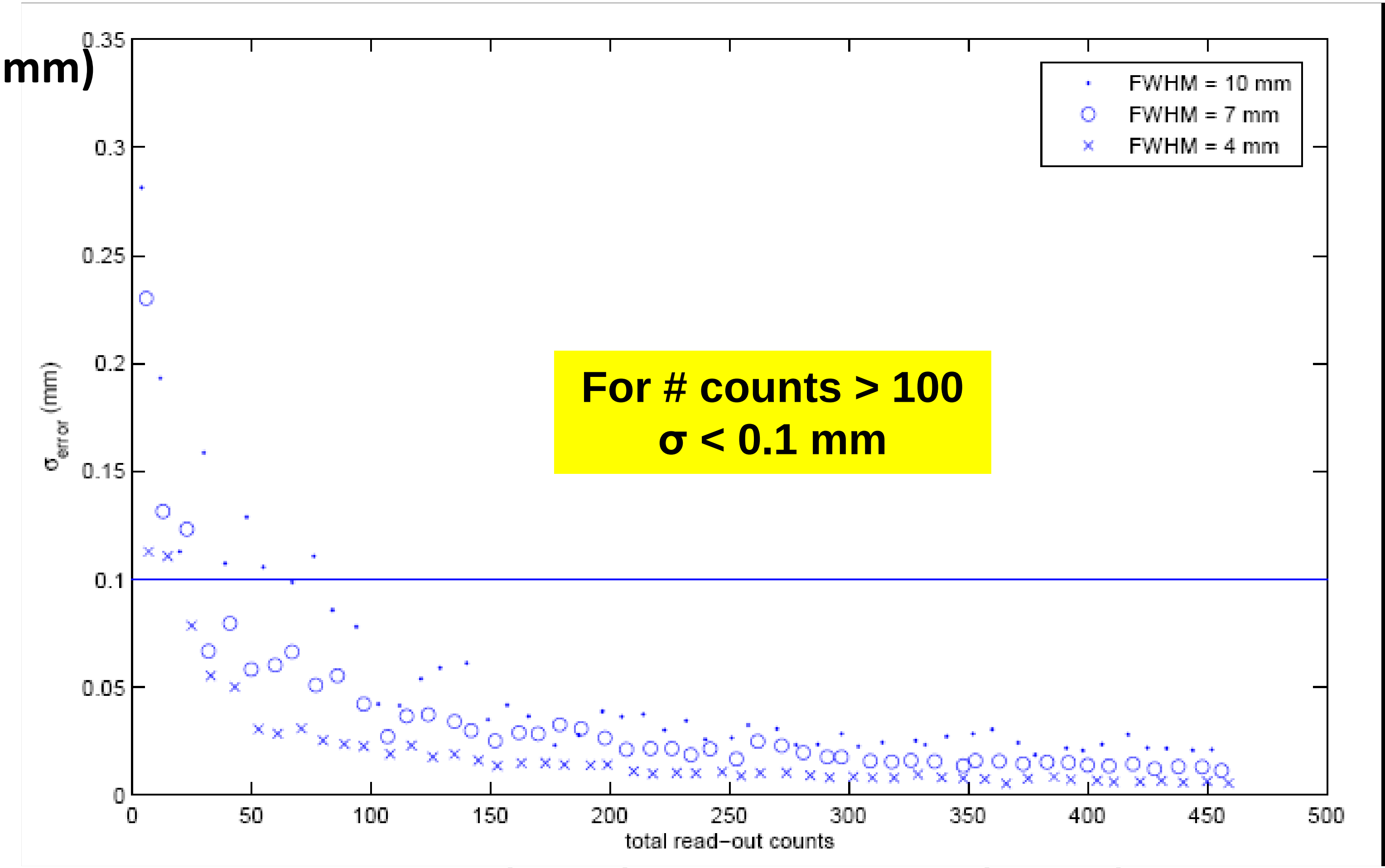
$$Error \propto \frac{1}{\sqrt{S_i}}$$

Standard deviation of the error on position measurement as a function of the total counts for proton beams with different dimensions (FWHM 10 mm, 7 mm e 4 mm).

Minimum time to collect 100 counts: 100 μs
→ Beam intensity of 10^{10} protoni e $4*10^{8}$ carbon ions

100 counts = 20 pC

σ_{err} (mm)

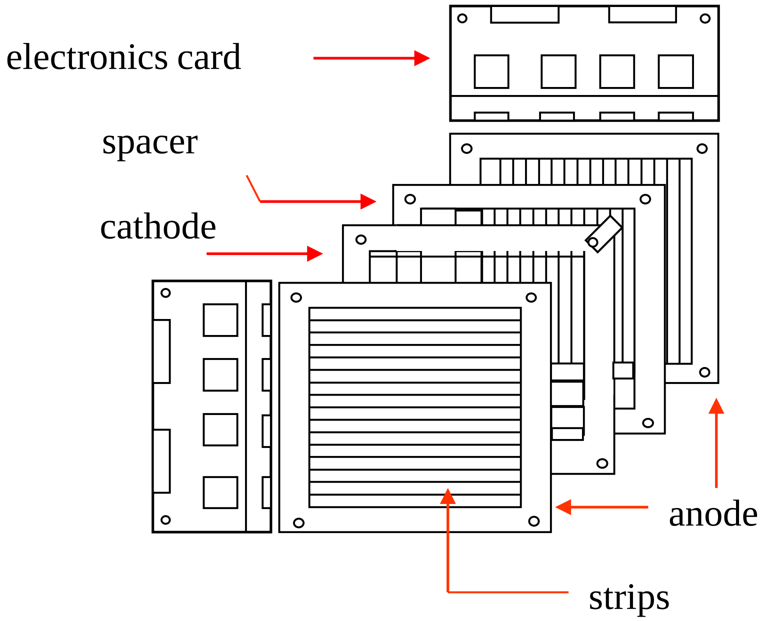


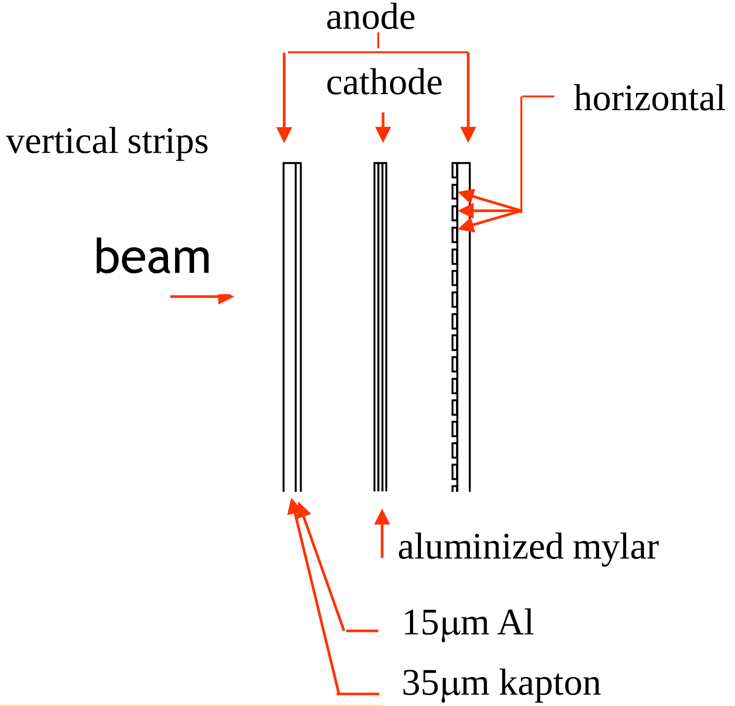
For # counts > 100
σ < 0.1 mm

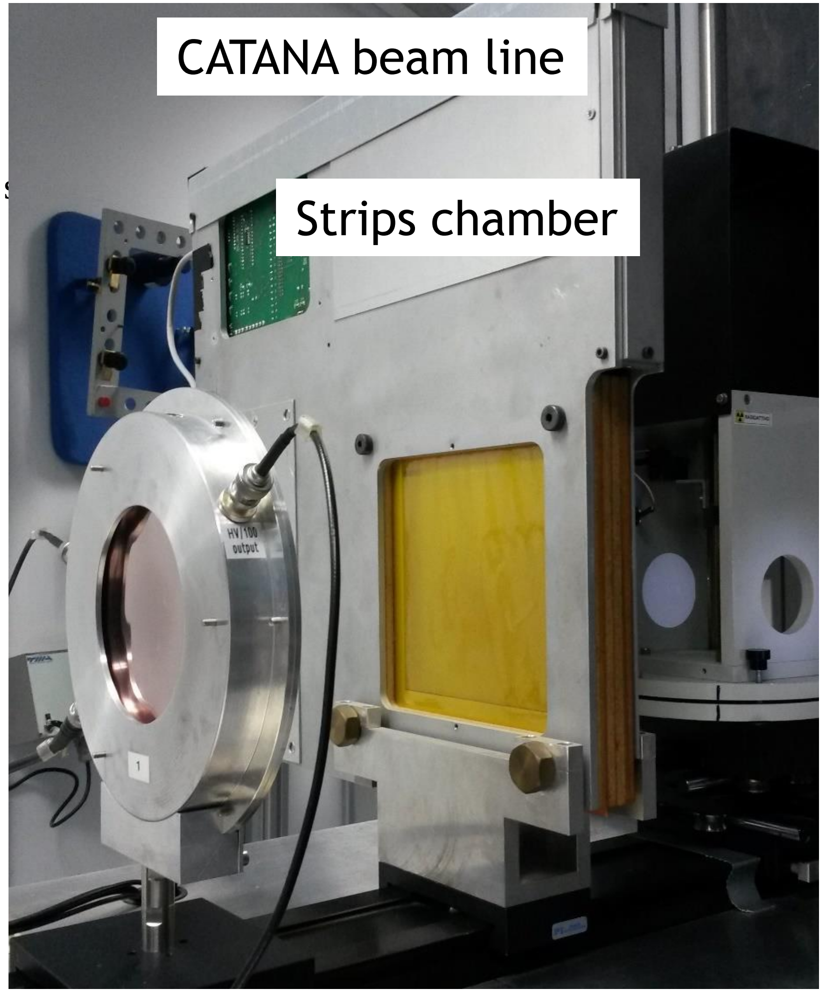
Total readout counts per channel

Strip chamber for small scattered field: example

2 ionization chambers with anode segmented in strips (x,y)







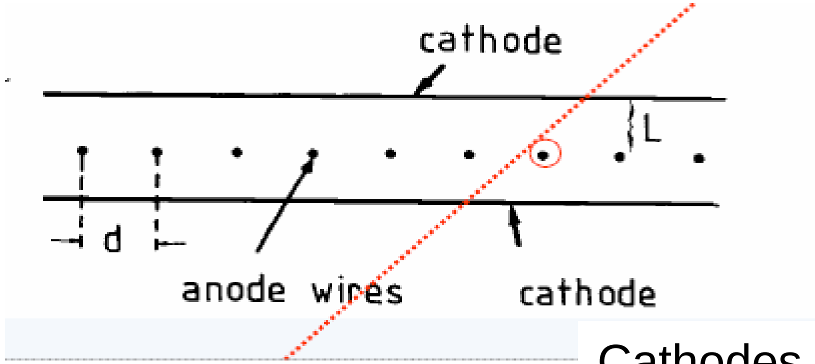
Sensitive area →	12.8X12.8 cm^2
Total thickness	~ 200 μm water equiv. thickness
Number of strips/chamber →	256
Strip width →	400 μm
Pitch →	500 μm
Readout rate →	up to 4 kHz (1 Hz)

N. Givechi et al, "Online beam monitoring in the treatment of ocular pathologies at the INFN Laboratori Nazionali del Sud-Catania" Physica Medica (2011) 27, 233e240

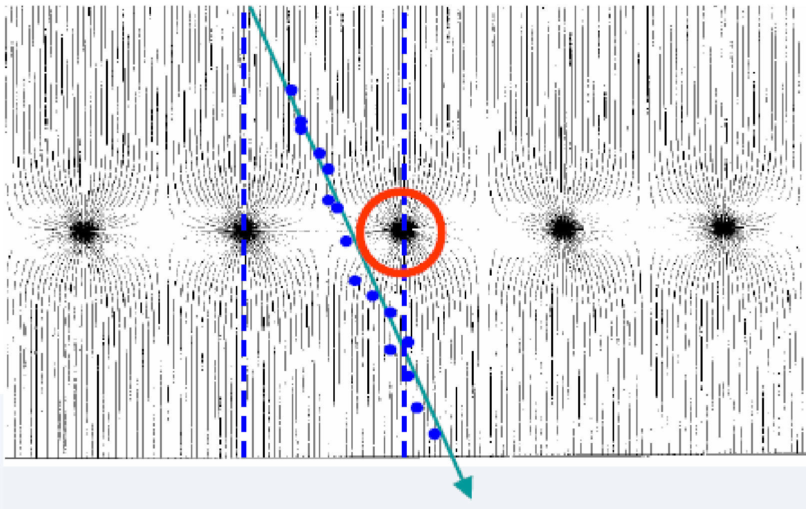
Beam monitors to measure position and width: multi-wire ionization chambers

$a << d < L$

a = wires radius

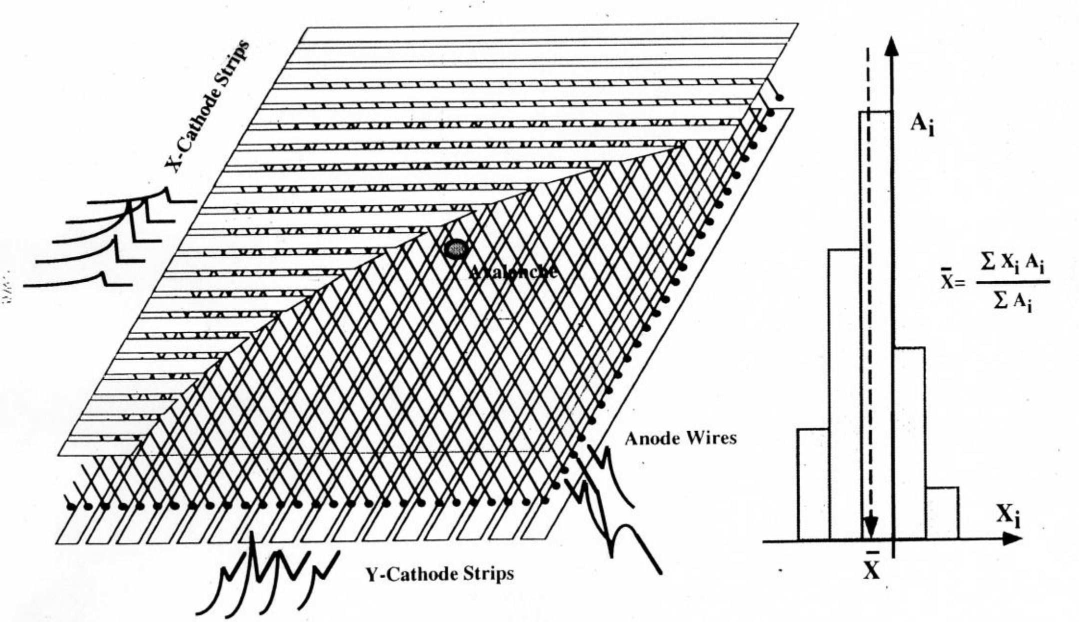


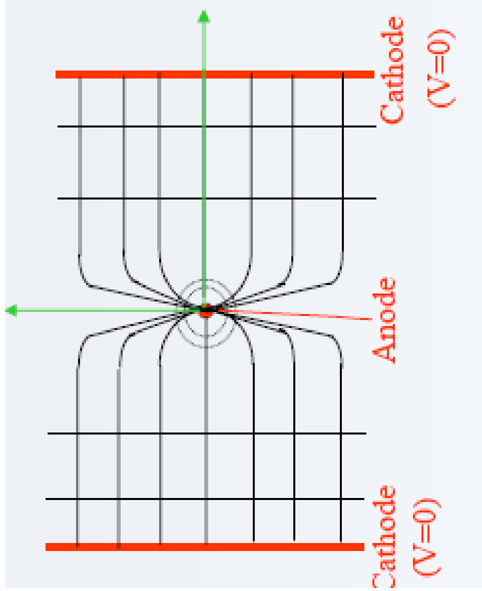
$a = 10\ \mu m$
$d = 2\ mm$
$L = 8\ mm$



Cathodes at V=0
Anode (wires) at $+V_0$

Like strips: 1 coordinate for each wire direction





Each particle provide a current only in the closest wire

Spatial resolution with Center of gravity < 1 mm (depend on distance d)

Multi-wire ionization chambers at NIRS (Chiba)

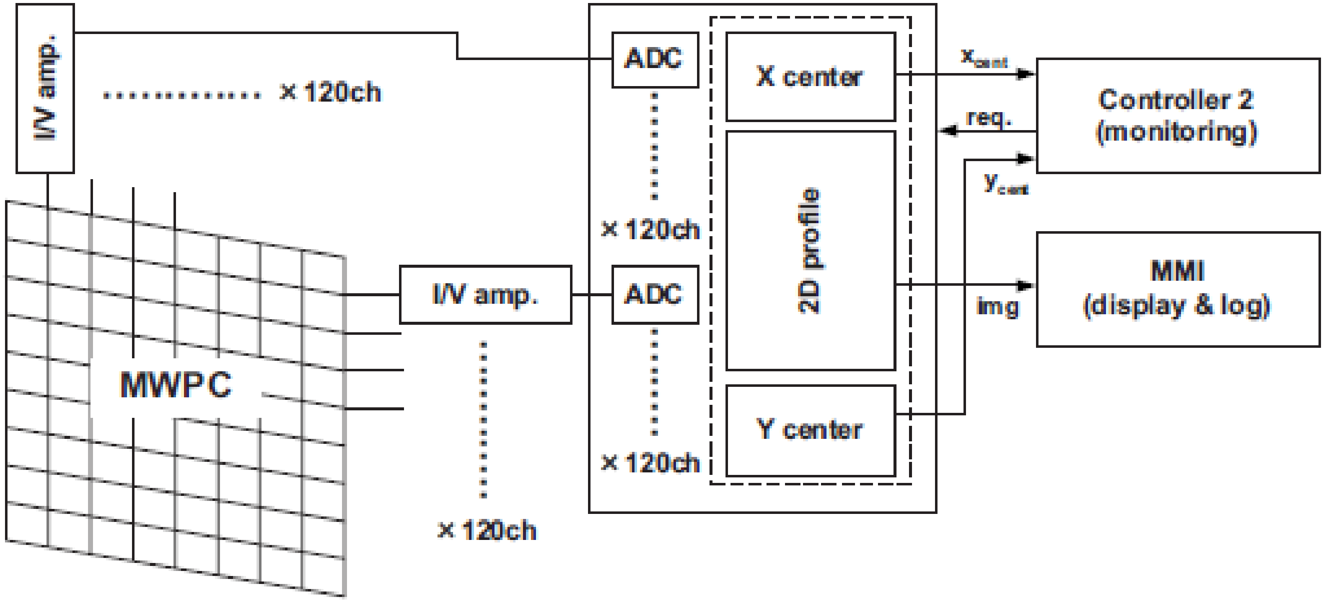


FIG. 4. Schematic drawing of beam position monitor and its electronics.

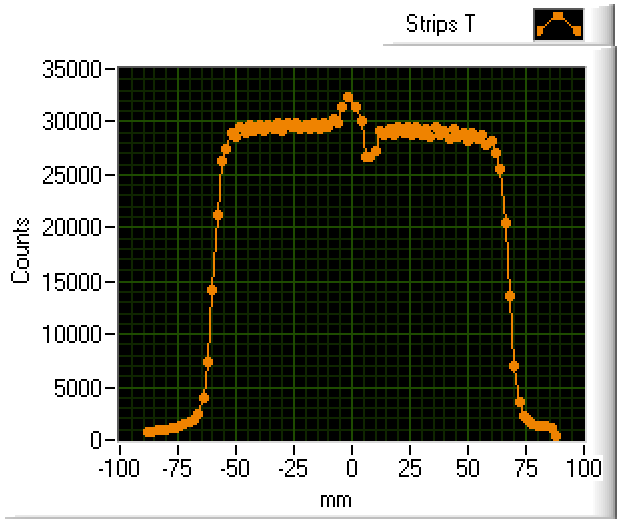
With the anode wire spacing of 2 mm, this MWPC has 120 anode wires for *x* and *y* planes, respectively. Anode-cathode distance is designed to be 3 mm to avoid any gain drops due to the space charge effect. Diameters of the cathode and anode wires are 50 and 30 μm, respectively

Furukawa *et al.*: Fast scanning system for heavy-ion therapy
Medical Physics, Vol. 37, No. 11, November 2010

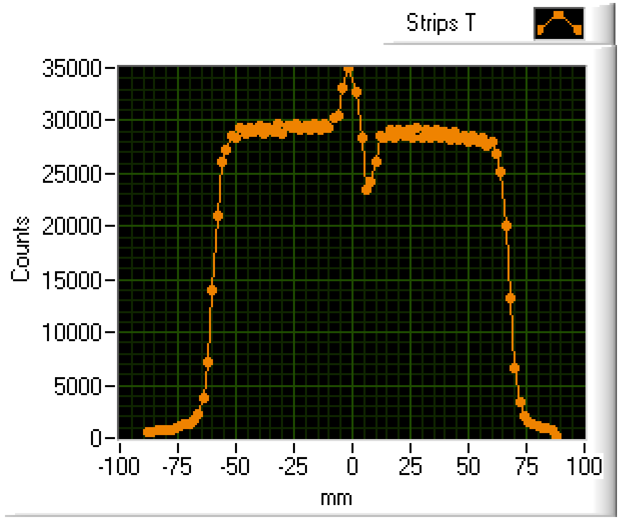
With spot scanning the beam position errors affect dose uniformity

Spot position error affect dose uniformity: example of 1, 2 and 3 mm of deviations on square field for beam dimension of 7 mm FWHM

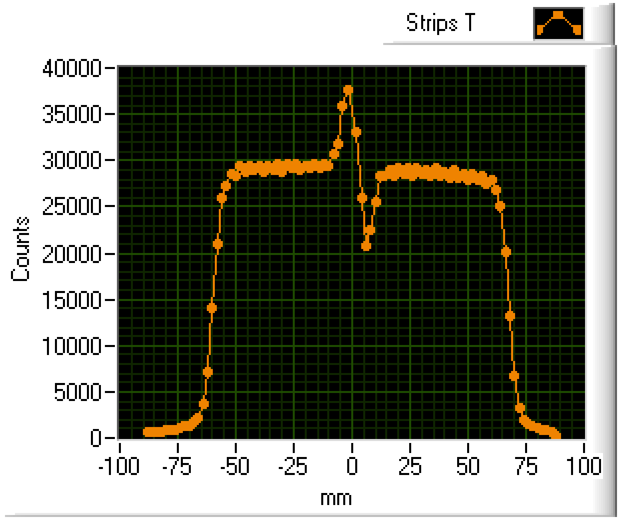
Lateral field profile



1 mm deviation



2 mm deviation

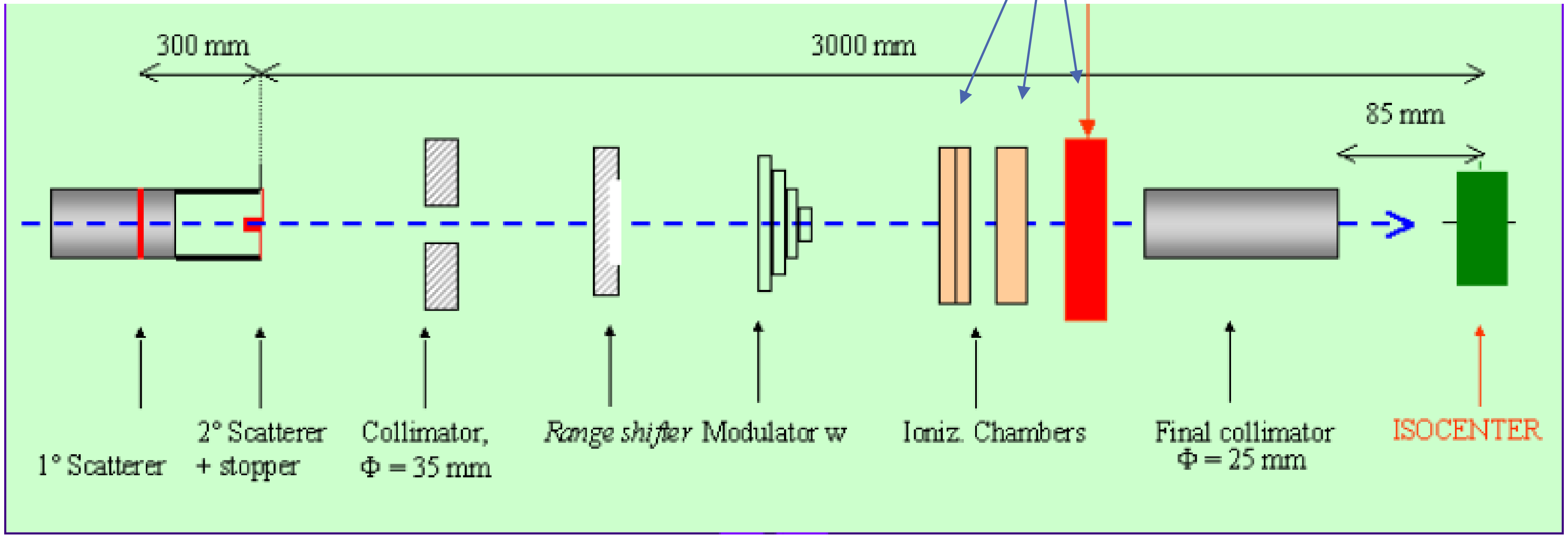


3 mm deviation

Beam monitor for scattering systems

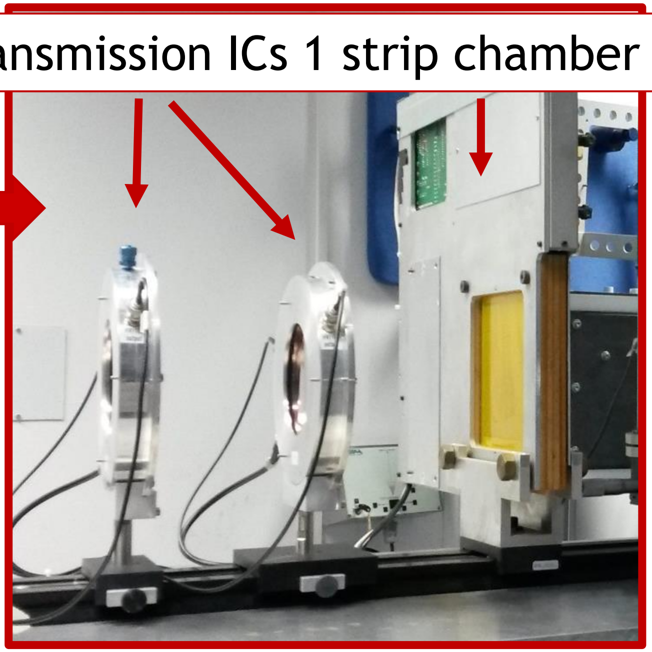
A few differences from scanning systems

Beam monitors before the collimators



Catana beam line for ocular treatments

2 Transmission ICs 1 strip chamber

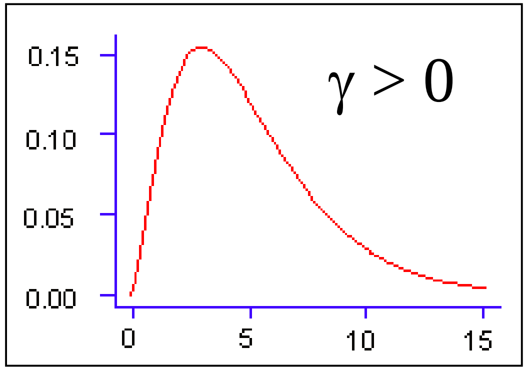


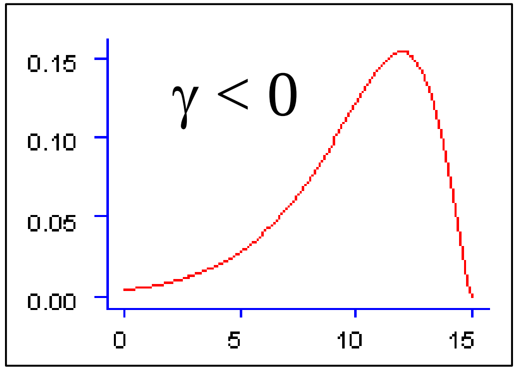
Symmetry check for scattering systems

Proton beam symmetry check ⇨ **skewness** measurement

$$\gamma = \frac{\mu_3}{\sigma^3}$$

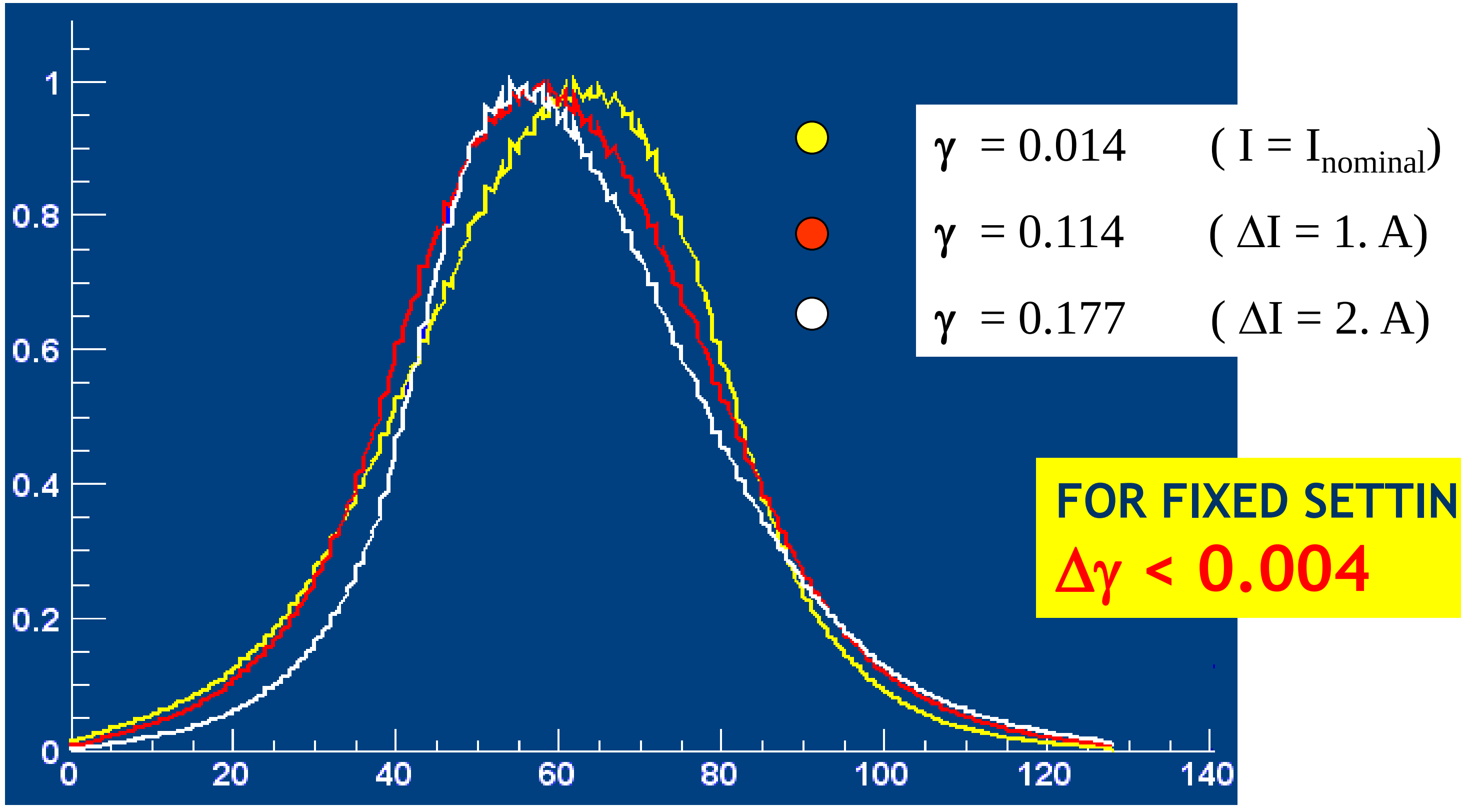
$$\mu_3 = \frac{\sum_{i=1}^{N} c_i \cdot \left(x_i - \bar{x}\right)^3}{\sum_{i=1}^{N} c_i}$$





Unstable beam conditions

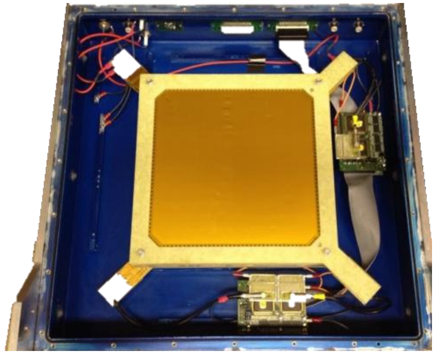
skewness changes with changing beam conditions
measured for 3 current settings of beamline steer. magnet

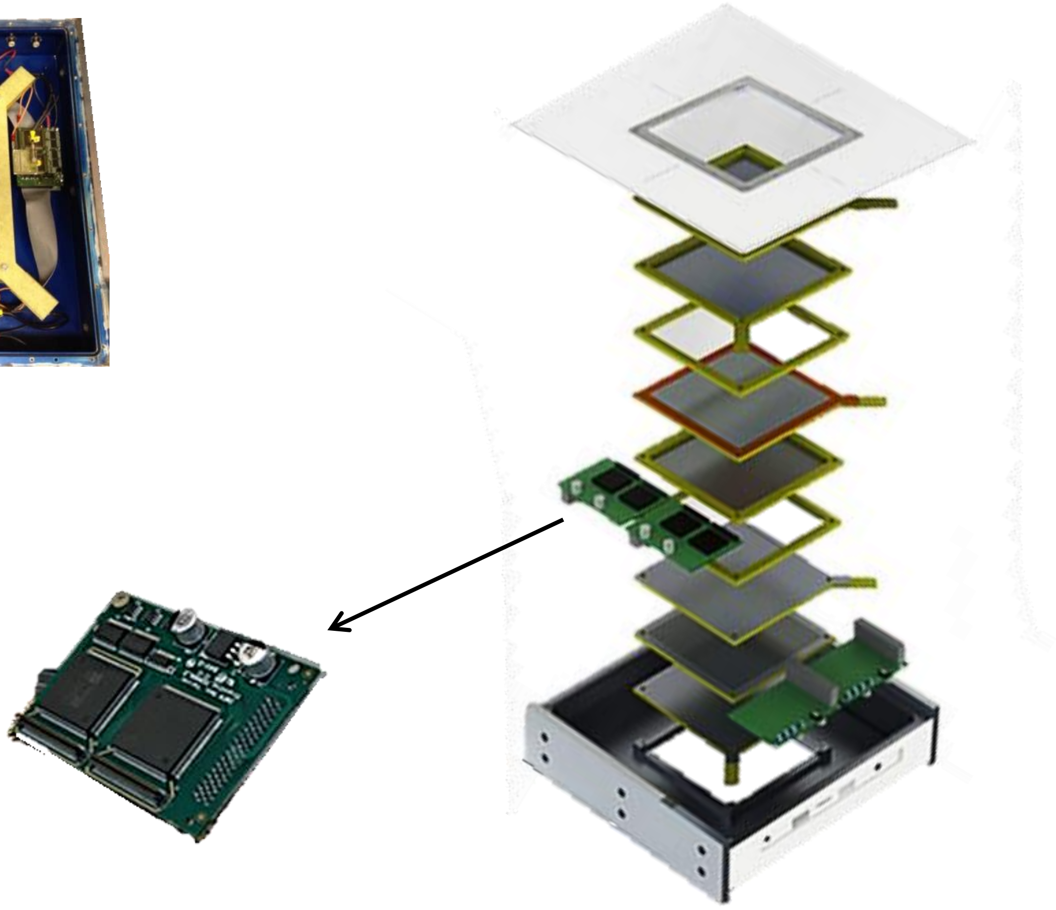


FOR FIXED SETTINGS BEAM
$\Delta\gamma < 0.004$

Detector readout

The Analog signal i(t) to digital signal (counts)





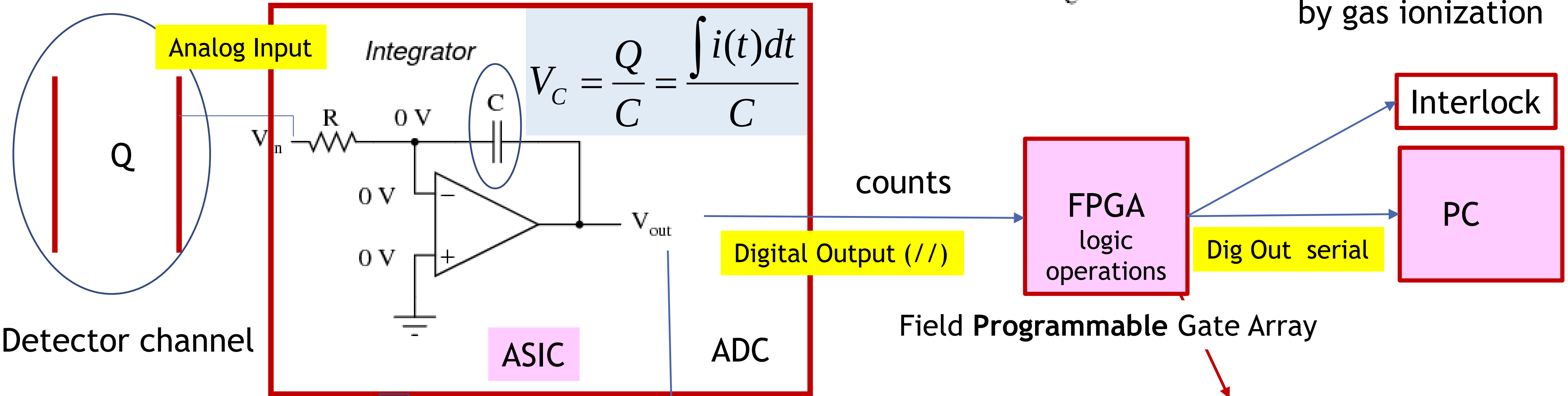
Dedicated readout electronics to measure the ionization currents

Detector readout

$Q = \int i(t)dt$ Analog signal i(t) to digital signal (counts)

$\Delta V = \frac{\Delta Q}{C}$

Charge produced by gas ionization



$$V_C = \frac{Q}{C} = \frac{\int i(t)dt}{C}$$

Detector channel

ASIC

ADC

counts

Digital Output (//)

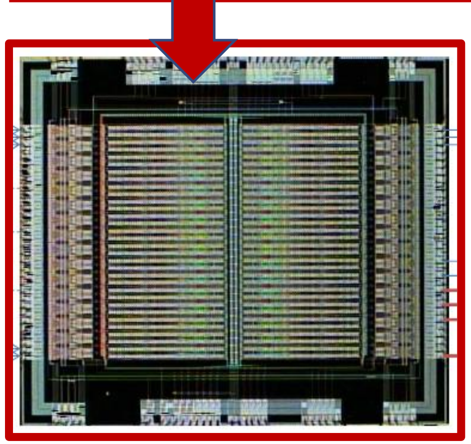
FPGA
logic
operations

Dig Out serial

Interlock

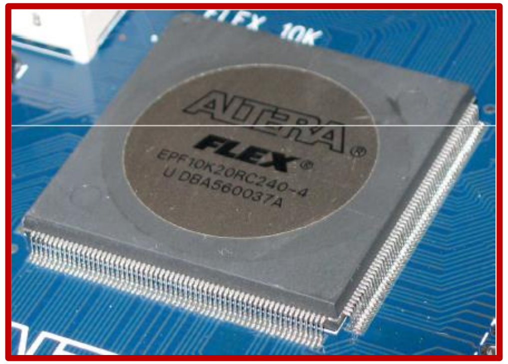
PC

Field **Programmable** Gate Array



Application
Specific
Integrated
Circuit

Vout = Vc → we measure Vout
→ proportional to Q produced by the particle in the detector
→ proportional to the Number of particles that cross the chamber
→ Proportional to the Dose



DD Control concept

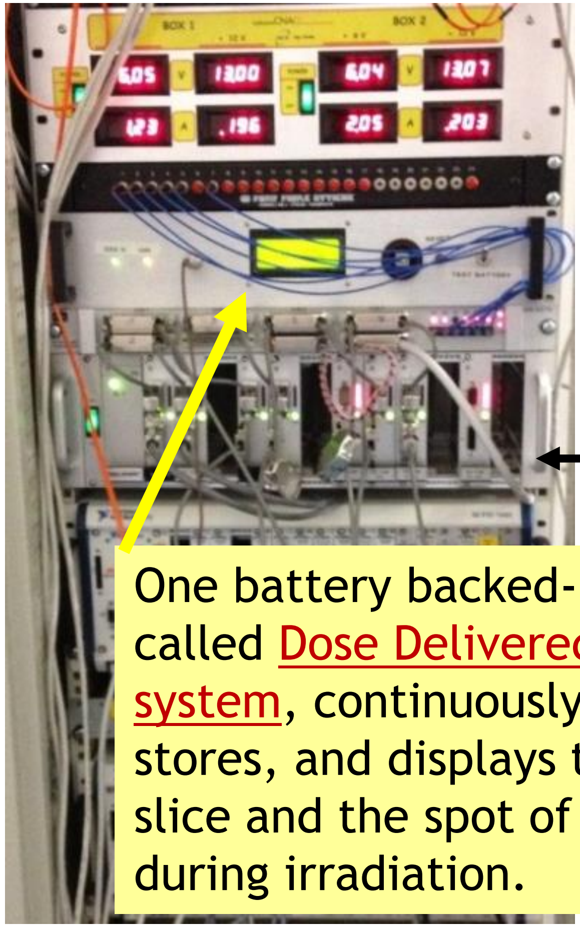
A patient is not a target used for physics experiments

A safe and accurate Dose Delivery System is required together with

A dedicated Therapy (or Patient) Control System

The CNAO Patient Interlock System (PIS)

At CNAO the safety of the treatment mainly relies on two interlock systems: Patient interlock system (PIS) and Safety interlock System (SIS). These systems collect any error conditions and either force the immediate interruption of the beam delivery or inhibit the operations as long as the conditions persist.



DDS interface with PIS

One battery backed-up device, called Dose Delivered Recovery system, continuously receives, stores, and displays the last treated slice and the spot of each slice during irradiation.

The PIS is dedicated to the patient safety by acting on the beam chopper to interrupt the treatment when an interlock occurs.

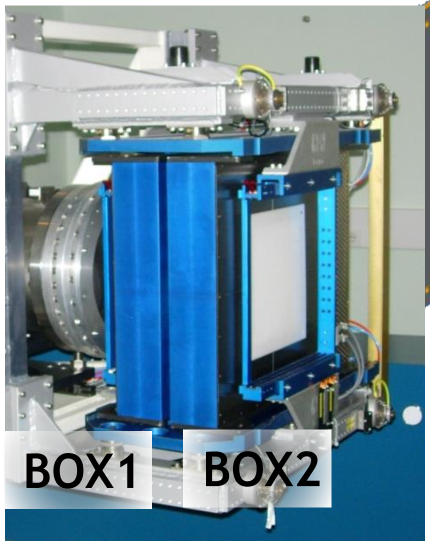
It manages short interruptions (a few seconds) and treatment terminate and recovery

Critical condition	Tolerance intervals
|QInt1-QInt2|	< 100 counts
|QInt1-QInt2|/QInt1	< 10%
Beam intensity (protons)	$< 3 \times 10^{10}$ protons/s
Beam intensity (C ions)	$< 5 \times 10^{8}$ C ions/s
Spot position deviation in X	< 2 mm
Spot position deviation in Y	< 2 mm

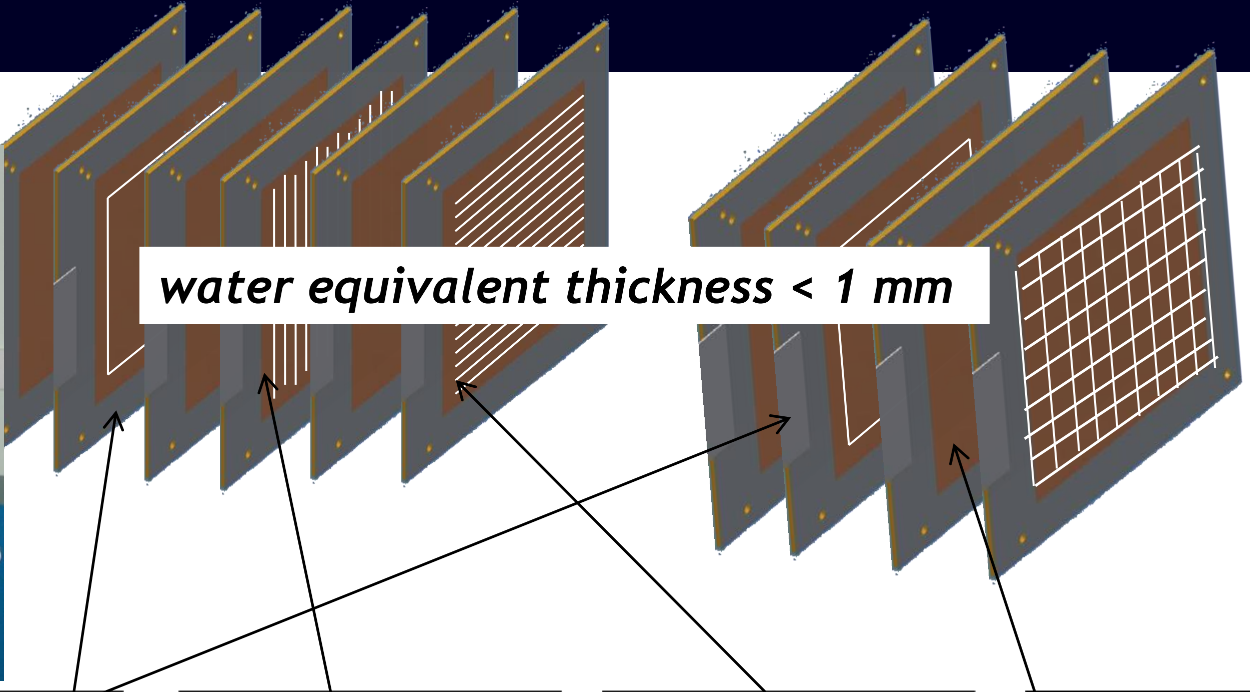
List of the main CNAO DDS interlocks with tolerance intervals in use. QInt1 and QInt2 are the number of counts measured by the 2 integral chambers; each count corresponds to 200 fC.

DDI worldwide (for scanning system)

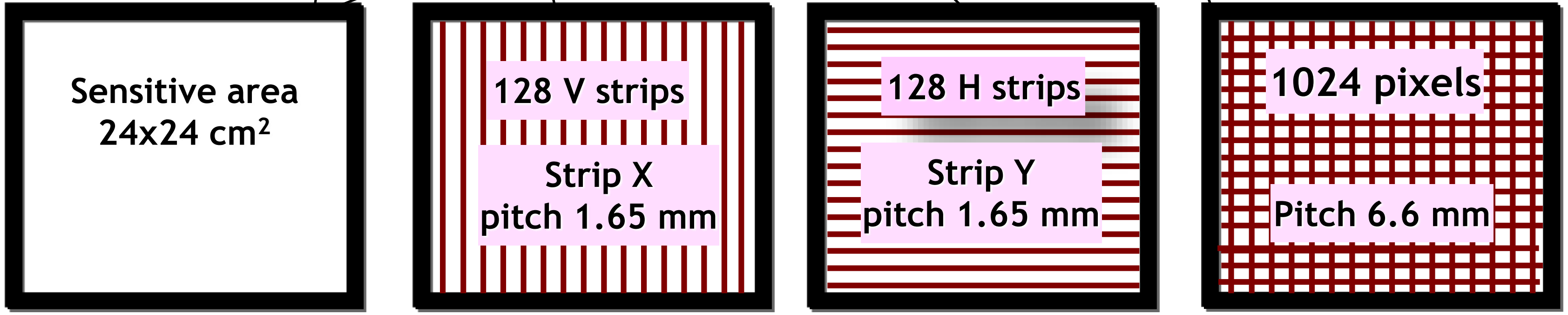
The CNAO beam monitor



Electrodes in BOX1


water equivalent thickness < 1 mm

Electrodes in BOX2


Sensitive area 24x24 cm^2

128 V strips

Strip X pitch 1.65 mm

128 H strips

Strip Y pitch 1.65 mm

1024 pixels

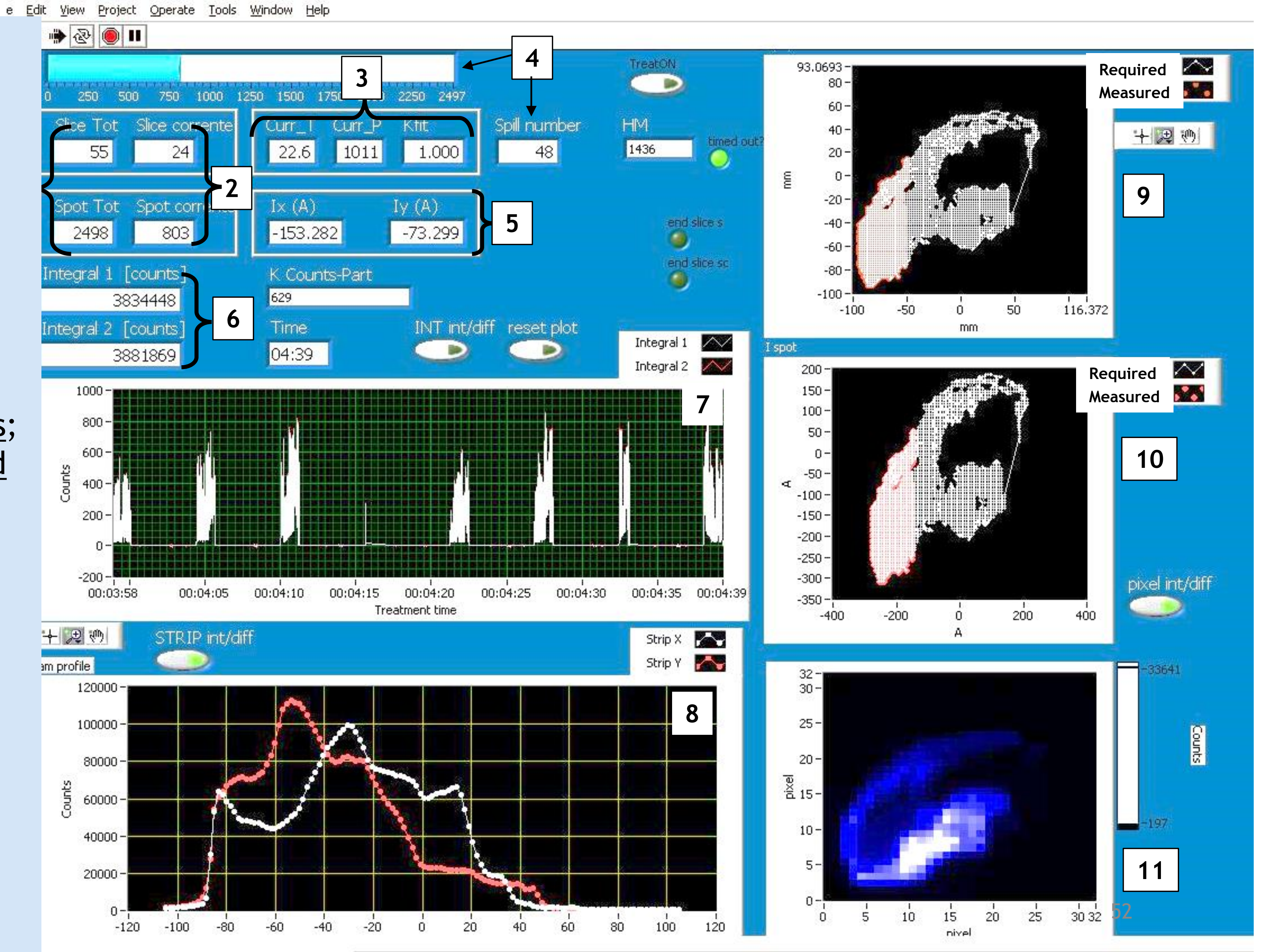
Pitch 6.6 mm

Strip and Pixel sensitive area 21x21 cm^2

TERA 08 for fluence measurement
- VLSI CMOS 0.35 µm
- Bipolar input
- Digital output: 32 bit
- Clk 100 MHz
- Max counting rate 20 MHz
- Charge quantum: 50 ÷ 350 fC
- Saturation current 4-7 µA

Ref. [9]

1 - total number of slices and spots of this field;
2 - slice and spot numbers under delivery;
3 - measured temperature, pressure, and the flux correction factor;
4 - number of the spill and delivery progress bar;
5 - PS current set-points;
6 - INT1 and INT2 total counts;
7 - flux measured by INT1 and INT2;
8 - StripX and StripY total counts;
9 - spot positions in millimetres;
10 - PS currents in ampere: measured (full dots covering partial field) and required (small dots covering the overall field);
11 - 2D flux measured by PIX chamber.



Slice Tot: 55
Slice corrente: 24
Curr_T: 22.6
Curr_P: 1011
Kfit: 1.000
Spill number: 48
HM: 1436
Spot Tot: 2498
Spot corr: 803
Ix (A): -153.282
Iy (A): -73.299
Integral 1 [counts]: 3834448
Integral 2 [counts]: 3881869
K Counts-Part: 629
Time: 04:39

PSI : Gantry 1 beam monitors

3 Transmission ionization chambers (TICs)

Beam Flux monitors: TICs M1, M2, (M3)
- Air
- Cathode: 20 µm Al
- Anode: 20 µm mylar + Al
- d = 5 (10) mm gap
- V = 2000 V
- Collection time < 100 µs
- kicker switching time 50 µs
- Delay → 0.5 of mean spot time

POSITION AND WIDTH monitors
Two strip chambers (U e T)
- Kapton 20 µm + Al
- Width strip 4 mm
- Position resolution < 0.5 mm
- Charge collection time ~ 0.8 ms
- -> wait 1 ms before reading scalers at the ena of the spot

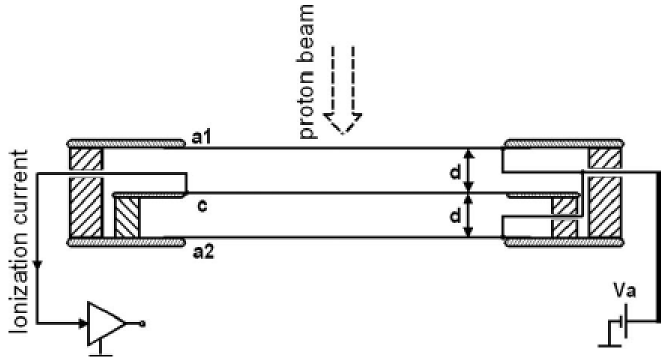
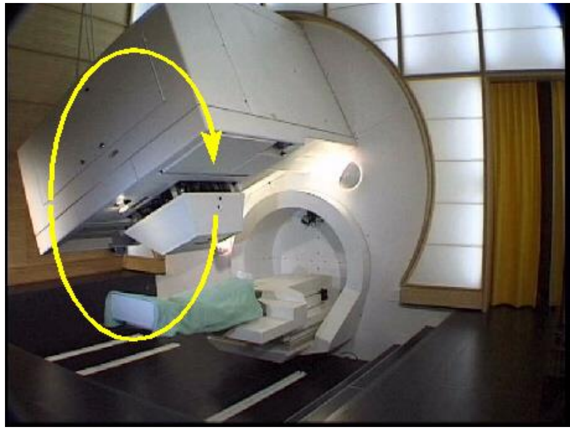
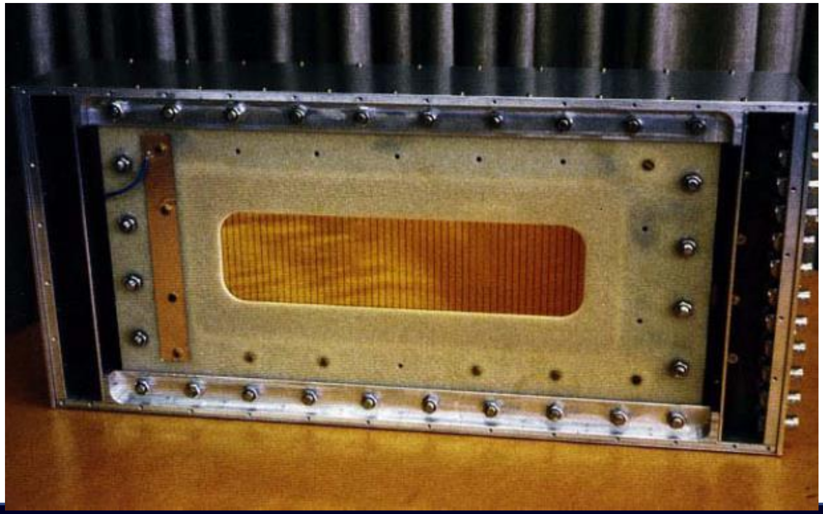


FIG. 5. Schematic representation of the parallel-plane ionization chamber (monitors 1 and 2). V_a (2000 V) is the applied voltage to the anodes (a1 and a2), and d is the spacing between the anode and the cathode (c). Monitor 1 has $d=0.5$ cm and monitor 2 has $d=1$ cm.

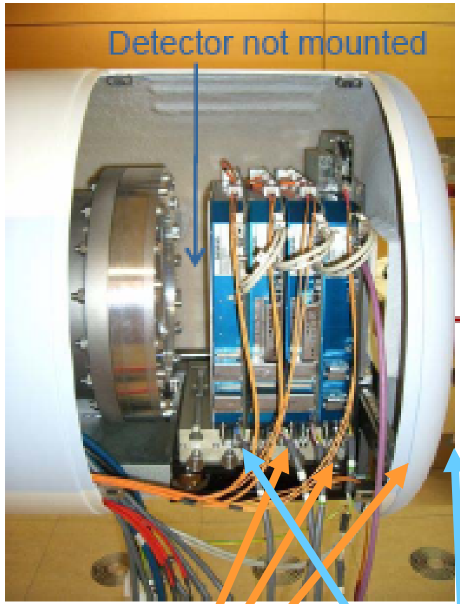


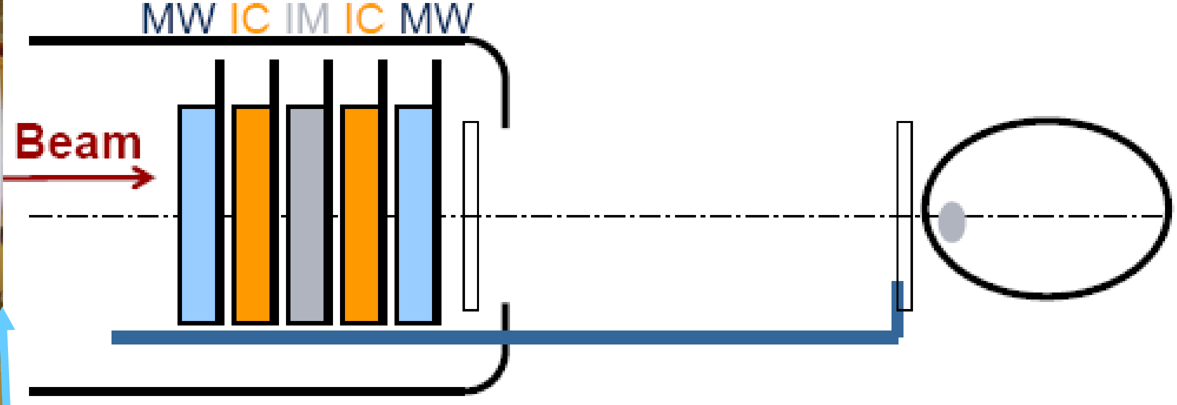
S. Lin, et al, "More Than 10 Years Experience of Beam Monitoring with the Gantry 1 Spot Scanning Proton Therapy Facility at PSI", Medical Physics 36(11) (2009) 5331



Siemens- HIT – GSI beam monitors in the nozzle

Detectors feedback for scanner





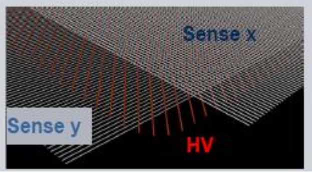
Ripple-filter Range-shifter

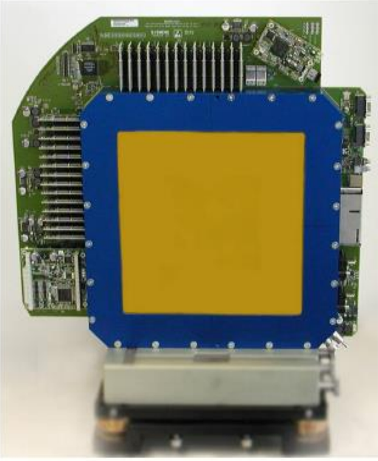
Optional Modulators Widen Iso-Energy-slices Decrease depth @ E_{min}

INTENSITY **POSITIONS**

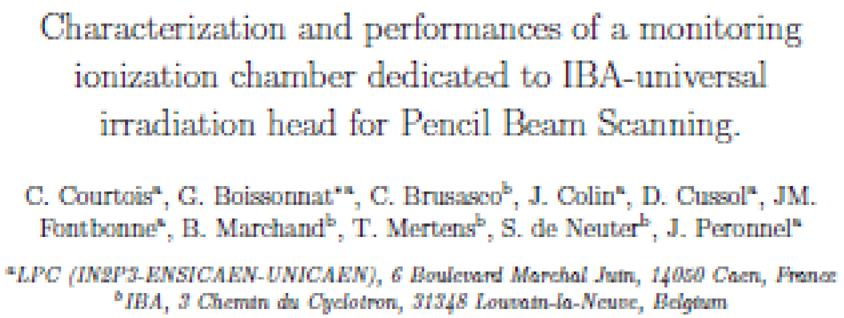
- Medical Detector (MDD-conform)
- Series Product
- Built by Siemens Healthcare
- Full integration of all aux. systems

112 channels / view
Aperture > 200mm x 200mm
Resolution ≤ 0,2mm





Beam monitors of the IBA – Pencil Beam Scanning System



Characterization and performances of a monitoring ionization chamber dedicated to IBA-universal irradiation head for Pencil Beam Scanning.

C. Courtois[a], G. Boissonnat[*a], C. Brusasco[b], J. Colin[a], D. Cussol[a], JM. Fontbonne[a], B. Marchand[b], T. Mertens[b], S. de Neuter[b], J. Peronnel[a]

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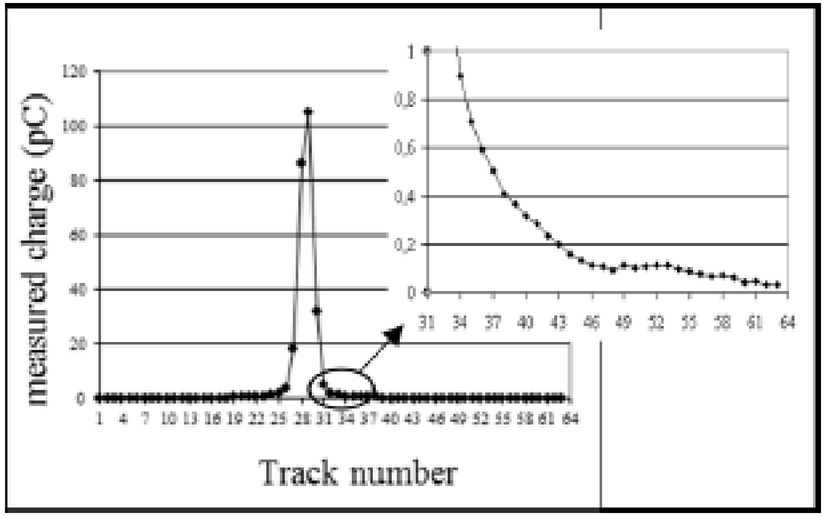


Figure 8: Beam transverse profile on x axis.

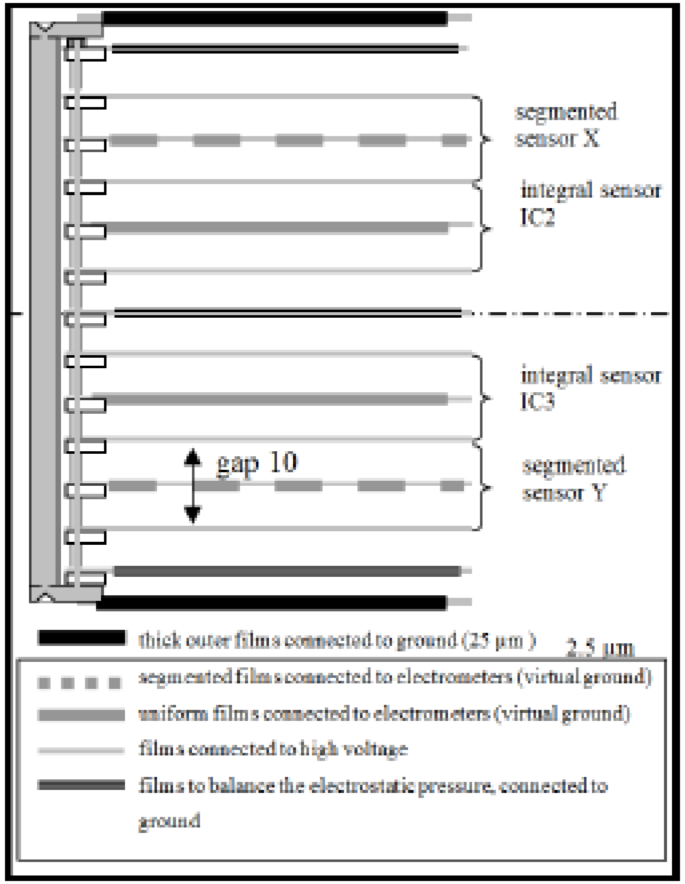
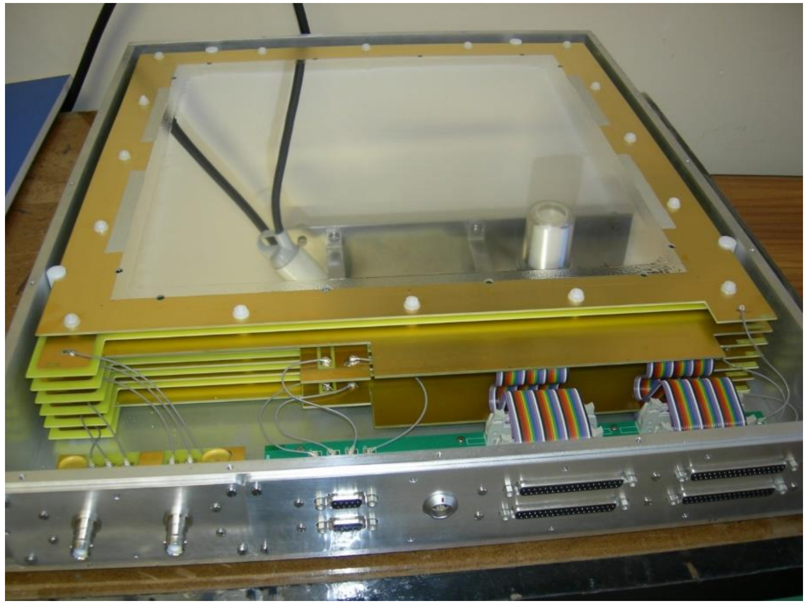


Figure 1: Vertical section of IC2/3.



Scattering vs Scanning nozzle: the MD Anderson examples

A. Smith, Med. Phys. 36, (2009)

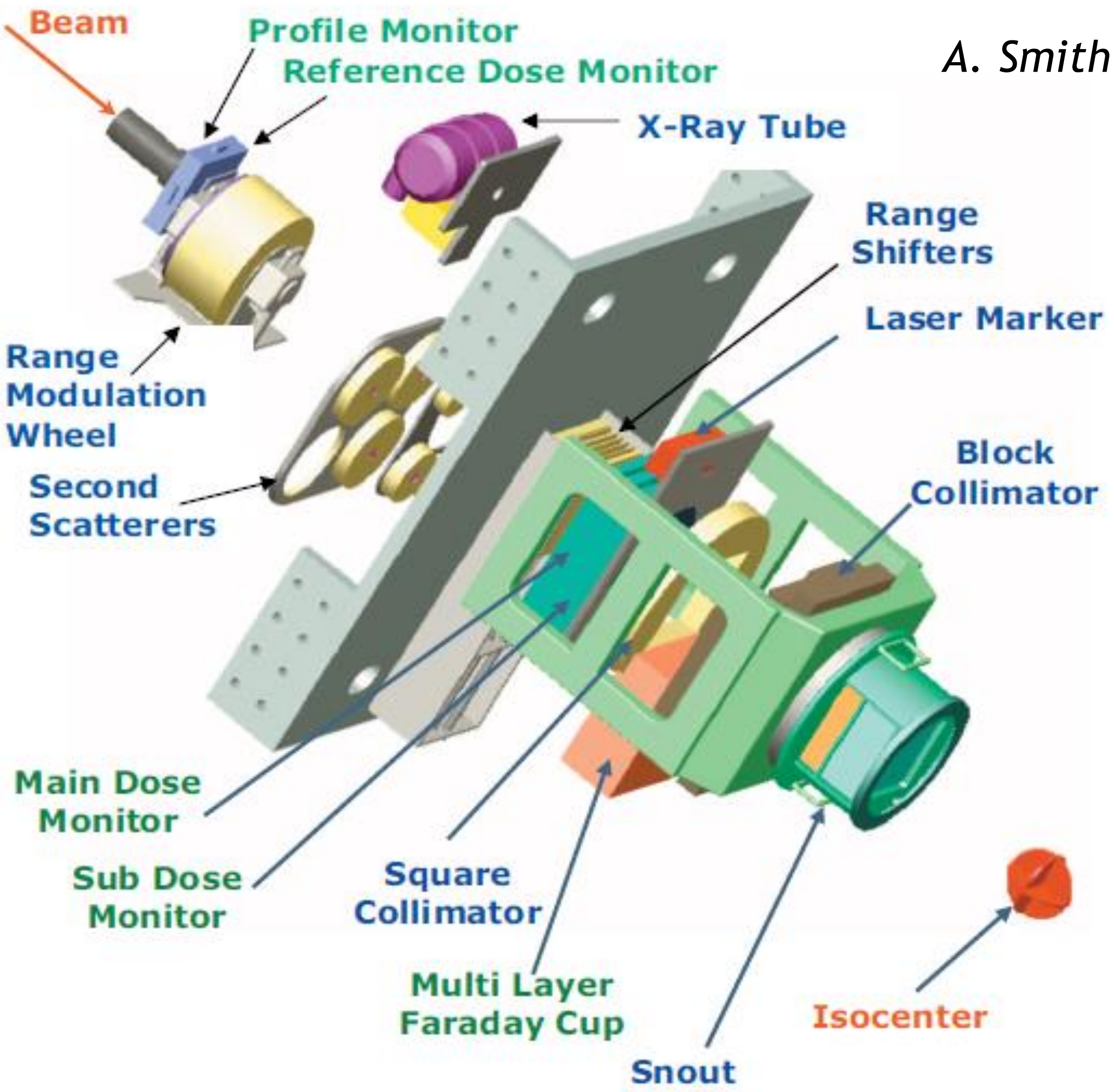


FIG. 3. Three-dimensional rendering of the passive scattering nozzle

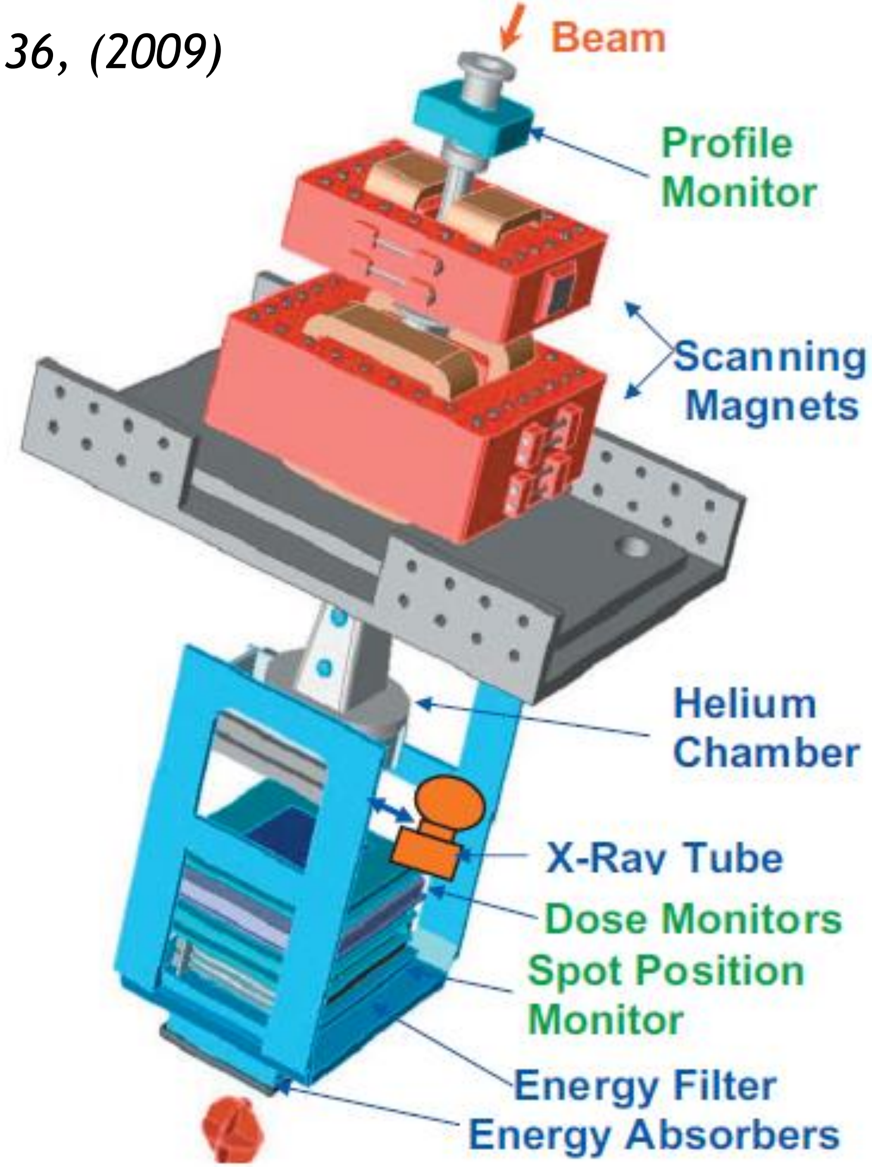


FIG. 4. Three-dimensional rendering of the scanning nozzle.

Future developments

Future developments

New detectors as beam monitor for next generation of accelerator that will deliver high flux pulsed beams

- Laser-driven accelerators
- Cyclinac
- Synchrocyclotrons
- Fixed Field Alternating Gradient accelerators

Typical Characteristics for high flux pulsed charged particle beams	
Pulse frequency (kHz)	0.2 – 1
Pulse Length (μs)	5 - 20
Number of particles per pulse (prot/pulse)	10^7 -10^8
Instantaneous Intensity (prot/s)	10^{12} -10^{14} (1nA-20μA)

Start-up and Integration of new in-vivo range verifications and imaging modality

> proton radiography/tomography
> PET activation
> Prompt photon imaging

On-line beam energy measurement

Pulsed beam specifications

- Pulse frequency: 1 kHz
- Pulse length: 10-20 μsec

For typical treatments to keep the overall treatment time in the few minutes ballpark:

- (1-2) x 10^8 protons/pulse which corresponds to:
- an average current during the pulse of (1.3-2.6) μA

Such intensity requires to improve the detectors used to monitor in real time the beam:

New DETECTORS and new READOUT are REQUIRED

Two solutions for beam monitoring have been envisaged:

- modified ionization chambers → To solve the issue of recombination
- scintillator plate

Final remark

We started from "standard" clinical requirements which are more or less the same for all the past end present centers

BUT

A REFERENCE or STANDARD DOSE DELIVERY SYSTEM DOES NOT EXIST

PSI Gantry 1

IBA Scanning (MGH – Trento - …)

CNAO - MedAustron

PSI Gantry 2

DDS for your CASE STUDY

NIRS-HIMAC

Varyan

Siemens (GSI-HIT-Marburg)

IBA Scattering (CPO – Paris)

MD Anderson

Thanks for your attention

INFN SEZIONE DI TORINO
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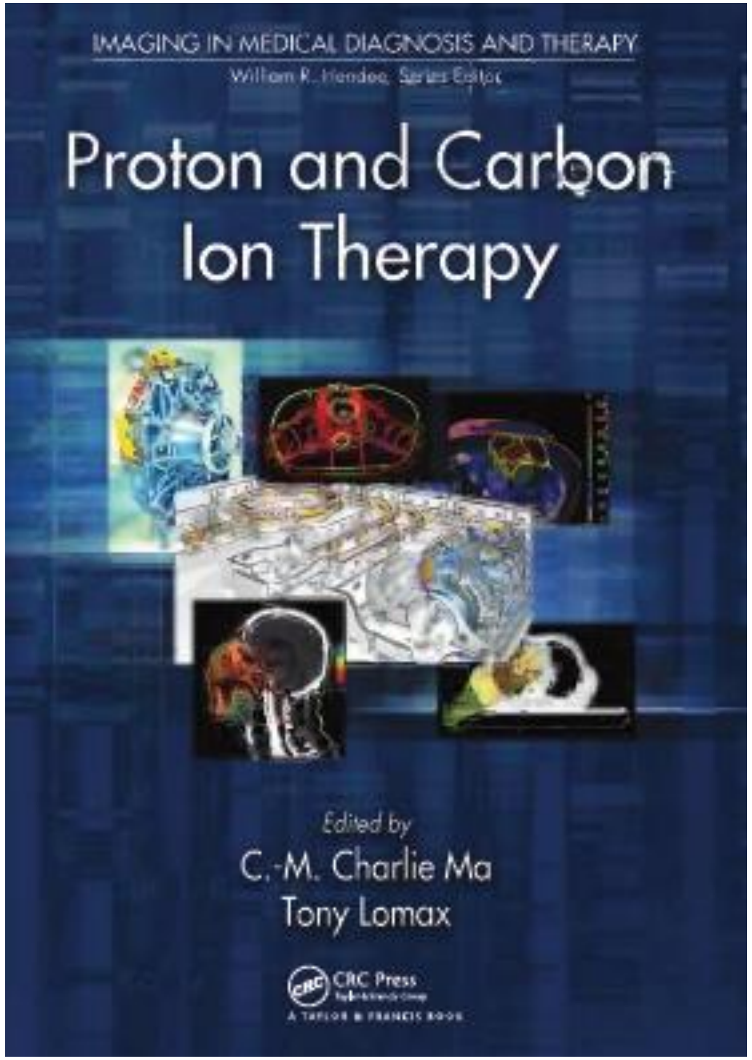
Books



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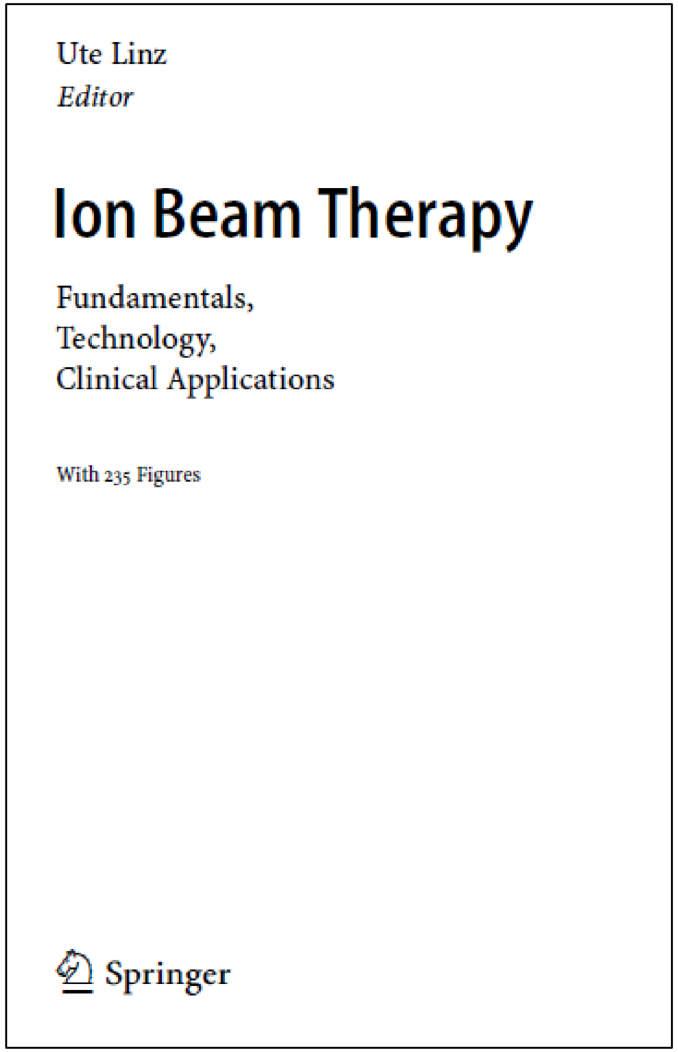

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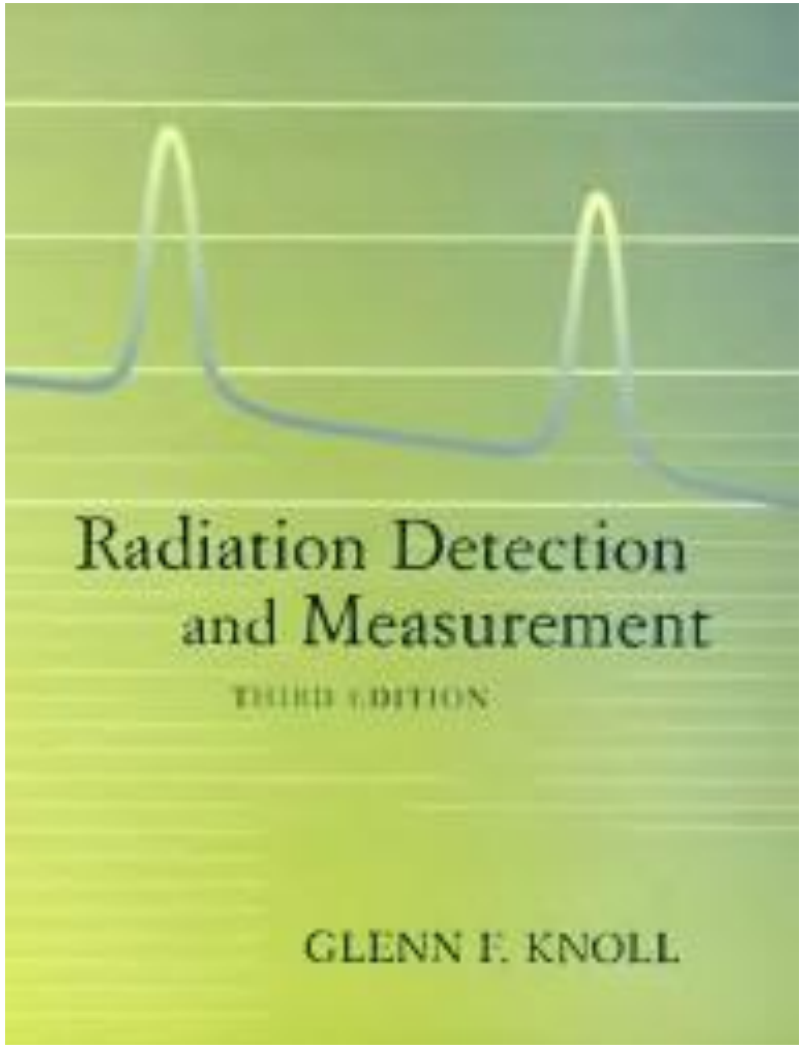

Radiation Detection
and Measurement

THIRD EDITION

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