New Tracking Gantry-Synchrotron Idea

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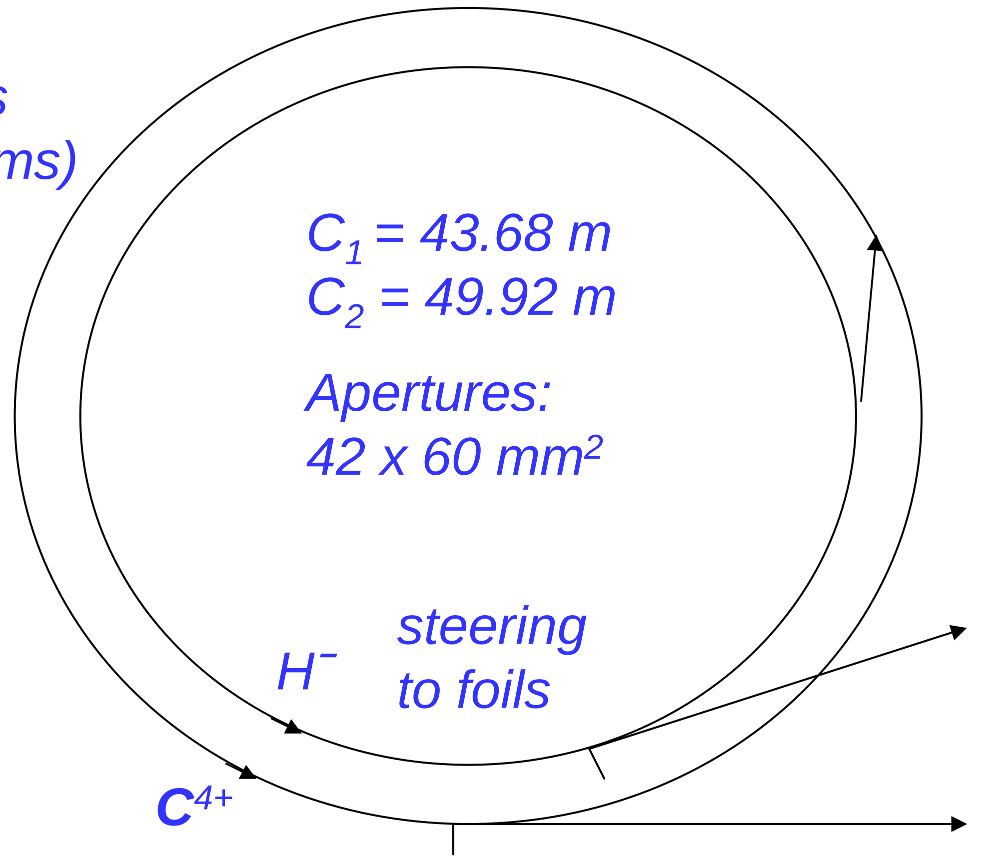
Scheme makes use of the following:

- *simple synchrotron and gantry magnet lattices*
- *series connection of magnets for 5 Hz tracking*
- *one main magnet P/S for ring, beam line & gantry*
- *stripping foils for wide energy-range extraction*
- *the full beam current in every scanning cycle*
- *full length tumour scanning in each 5 Hz cycle*
- *a single transverse scan in subsequent cycles*
- *minimizing the effect of the tumour movements*

Efficient, small aperture, 5 Hz rings



5 Hz synchrotrons
(low voltage rf systems)

$C_1 = 43.68$ m
$C_2 = 49.92$ m

Apertures:
42 x 60 mm^2

H^-

steering
to foils

C^{4+}

H^+
continuous
extraction
C^{6+}

***Inner ring:** H^- ions   5 - 250.0 MeV/u*

***Inner ring:** C^{4+} 4.965 - 31.18 MeV/u*

***RFQ linac** injector for H^- and C^{4+}*

***Outer ring:** C^{4+} 31.18 - 400 MeV/u*

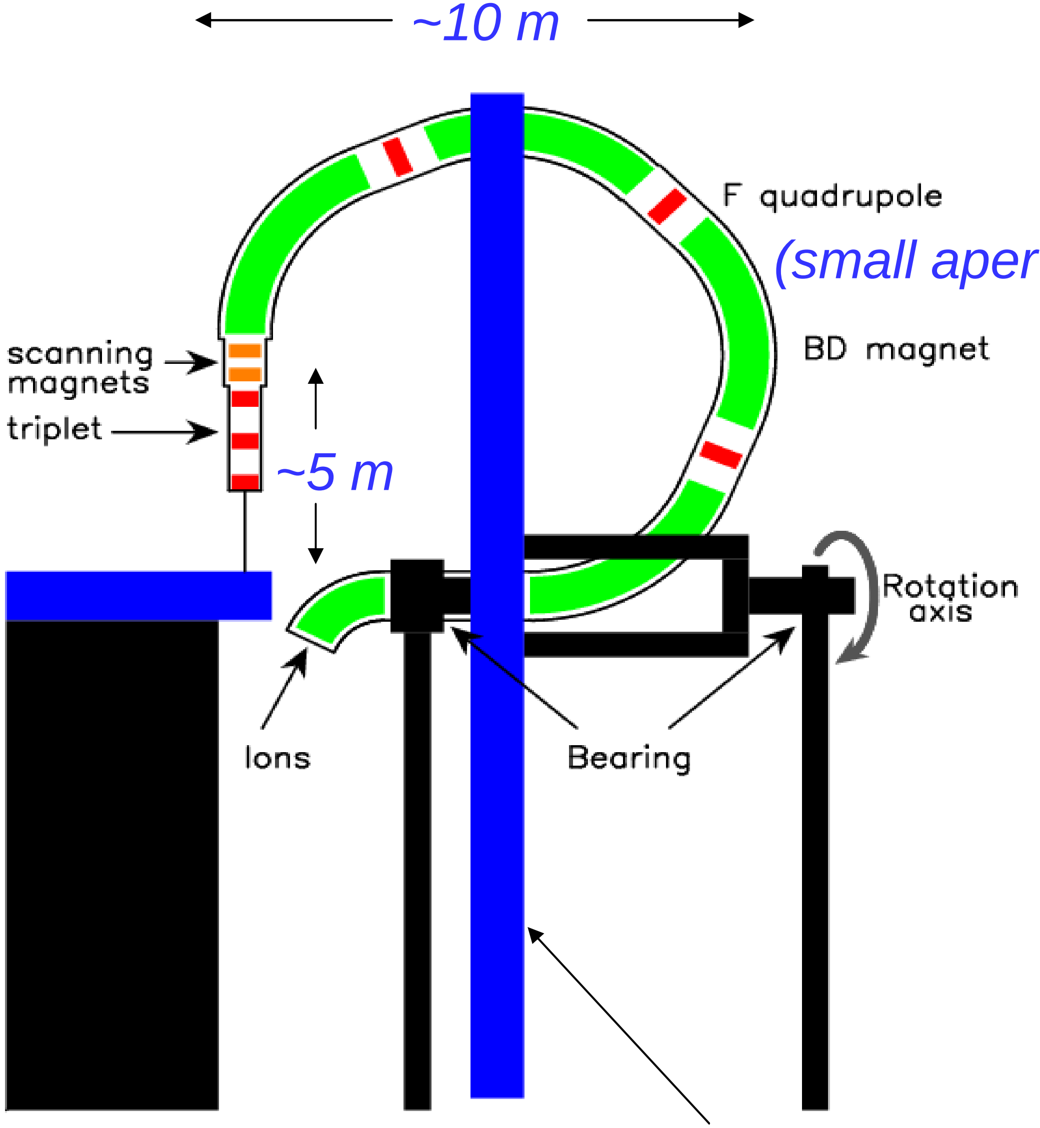
Features of the 5 Hz rings

- Each ring has six FODo combined function lattice cells
- Ring magnets have small (42 mm x 60 mm) apertures
- Injection of H^- or C^{4+} to Ring 1 is from a common RFQ
- Ring 1 has 1-turn H^- injection & outward stripping ejection
- Ring 1 has 1-turn injection for C^{4+} ions and fast extraction
- Ring 2 has fast inject of C^{4+} & inward C^{6+} stripping ejection
- Max. field in Ring 1 is < 5 kG for low, H^- Lorentz stripping
- Both rings require vacuum pressures of a few x 10^{-10} Torr

Basis of new gantry idea

- *Compact 3/4 ring gantry, with no reverse bends*
- *Magnets supported on both sides of a central, symmetrical, elliptically-shaped structure*
- *2π achromat of 4, identical, BD-o-F-o, hybrid cells*
- *Each BD is a vertical focusing, combined function magnet of length 4 m and bend angle 67.5°*
- *Quadrupole triplet (0.3 m) for adjusting output beam*

Conceptual, 2-π, 4-cell, gantry scheme



~10 m

(small aperture magnets)

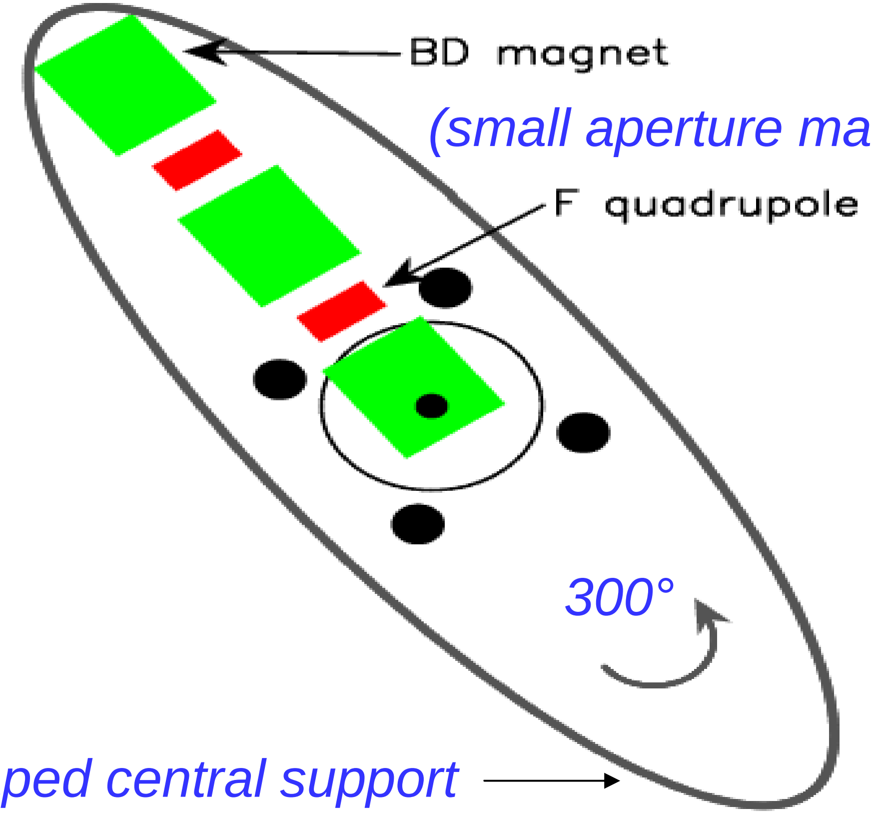
~5 m

(300°)

(**elliptically shaped central support **)

Downstream end view of conceptual gantry

a final triplet and one BD on upstream side



(small aperture magnets)

300°

elliptically shaped central support

Gantry features

- *A range of waists (β = 2.5 to 10.0 m) may be obtained at the gantry iso-centre by adjusting input Twiss parameters*
- *Bend fields and gradients of accelerators, beam line and gantry all have to track over the desired energy range*
- *Distances from last BD magnet and triplet lens to the gantry iso-centre are 5.0181 m and 2.0 m, respectively*
- *Scanning magnets are upstream of the output triplet, so there is no need for a large aperture, final BD unit*
- *The tracking bend magnet for beam entry from below requires acceptable stray field at patient platform*

Advantages over a traditional gantry

- *Simpler beam dynamics design*
- *Fewer number of magnet types*
- *All magnets of small aperture*
- *Shorter length for the structure*
- *More symmetrical arrangement*
- *Less flexing over angle range*

Note: May also serve as a traditional gantry
The angle range is restricted to ~300°

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H^+ & C^{6+} scans with 2.0 & 0.1 pnA (av)

- *Average beam power for H^+ & C^{6+} at peak energy is ≤ ½ W*
  Energy delivered In 20 sec, for $E_{av} = ½ E_{max}$, is ~ 5 joules
  If half reaches a litre tumour, dose received is 2.5 Gray

- *Assume overlap voxel scans for tumours 10 x 10 x 10 cm^3*
  and with a beam spot diameter at the patient of ~ 1 cm

- *At 5 Hz, full tumour is scanned over 200 pulses in ~ 40 s*
  or, scanning during field rise & fall, over 100 pulses in ~ 20 s
  Hence, at a single gantry angle, 2.5 Gray is delivered in 20 s

Scan times & doses for 1 litre tumours

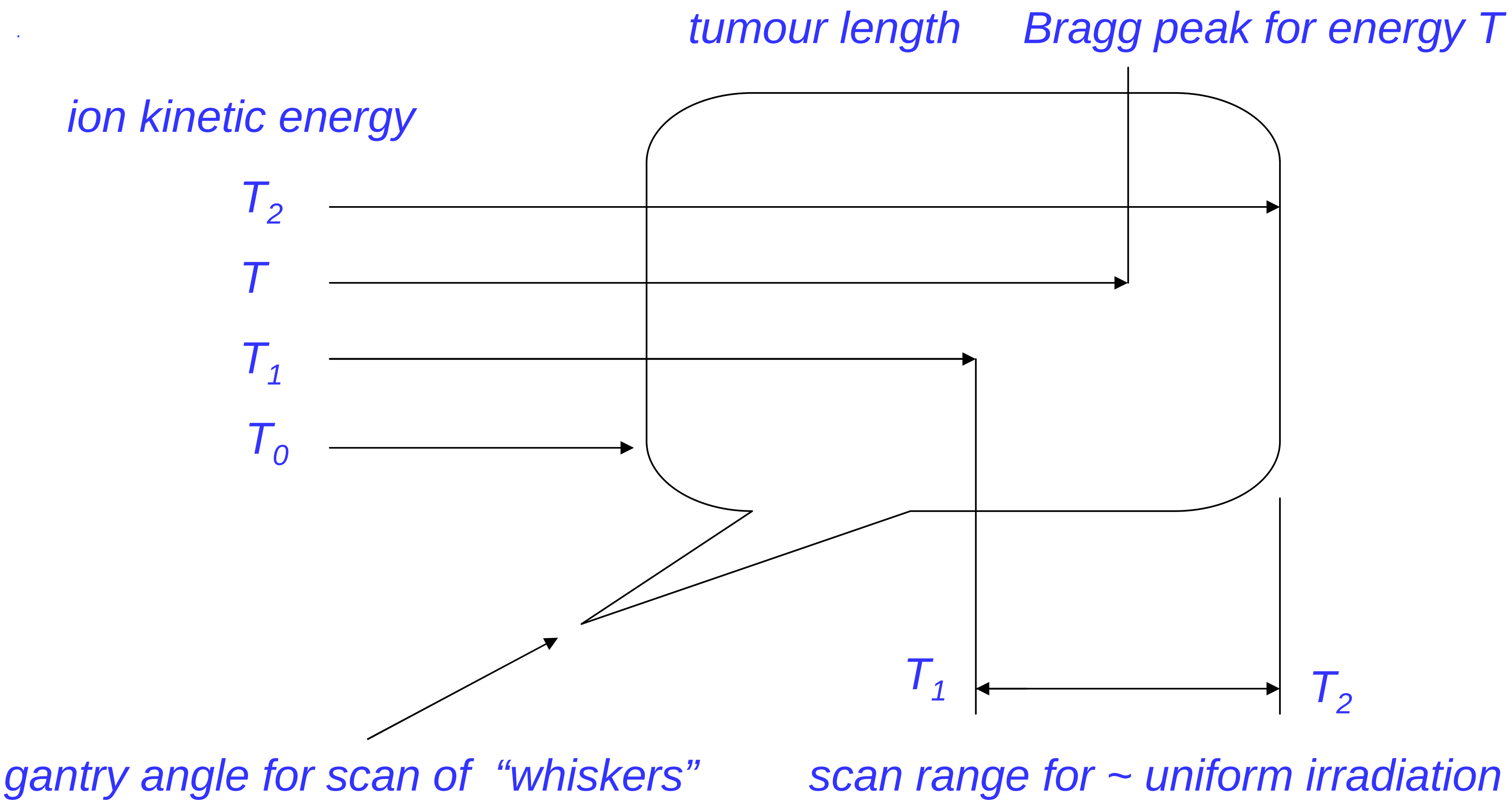
Length (cm)	*Section (cm^2)*	*Min. Scan time (s)*	*Dose (Gy)*
2.5	*20 x 20*	*80*	*10.0*
5.0	*20 x 10*	*40*	*5.0*
10.0	*10 x 10*	*20*	*2.5*
20.0	*20 x 2.5*	*10*	*1.25*

Dose required is reduced by the number of gantry angles used.

Max length dir'n gives fastest scan but most multiple scattering.

More overlapping & scan time may be used to increase doses.

Uniform tumour irradiation



tumour length

Bragg peak for energy T

ion kinetic energy

T_2

T

T_1

T_0

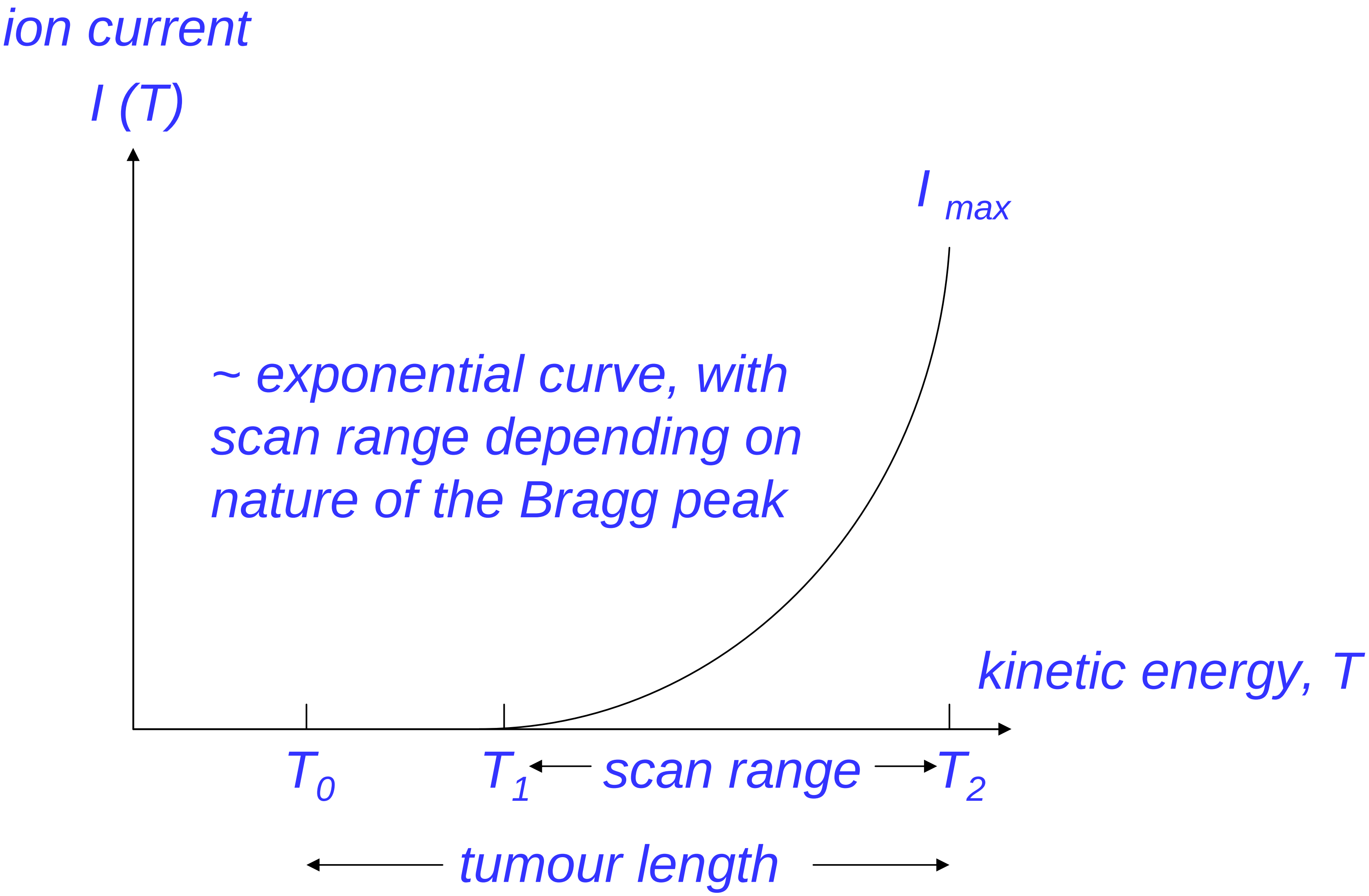
T_1

T_2

gantry angle for scan of “whiskers”

scan range for ~ uniform irradiation

I (T) vs T for uniform irradiation



~ exponential curve, with scan range depending on nature of the Bragg peak

Bragg peaks and ion beam therapy

If ionization loss in energy range was constant (no Bragg peak),
a δ-fn. current pulse at top energy would give a uniform dose !

Reality makes scanning with a gantry so desirable as:

- *single “uniform” scans give input healthy cells a high dose*
- *scanning uniformity for* H^+ *is affected by multiple scattering*
- C^{6+} *is better in this respect but ion fragments from the max. Bragg peak damage healthy cells beyond tumour.*

I(t) vs t needs to be programmed from cycle to cycle;
It isn’t as steep as I(T) vs T for sine wave guide fields.

Parameters for Synchrotron Rings

5 Hz Synchrotrons	Inner Ring (H^-)	Inner Ring ($C4^+$)	Outer Ring ($C4^+$)
Kinetic energy (MeV/u)	5.0 – 250.0	4.965 – 31.18	31.18 – 400.0
Circumference (m)	43.68	43.68	49.92
Gamma transition	1.57240	1.57240	1.57034
Minimum central field (T)	0.06321	0.18829	0.39795
Maximum central field (T)	0.47517	0.47517	1.55795
Maximum beta(v) value (m)	10.775	10.775	12.424
Maximum beta (h) value (m)	9.998	9.998	11.502
Maximum dispersion (h) (m)	3.641	3.641	4.182
3σ emittance εn ((π) mm mr)	1.250	1.250	1.250
Max. vertical beam size (mm)	22.50	22.50	24.50
Max. horiz. beam size (mm)	45.00	45.00	45.00
Max. aperture height (mm)	33.00	33.00	35.00
Magnet v x h gap size (mm^2)	42.0 x 60.0	42.0 x 60.0	42.0 x 60.0

Ring Acceleration Systems

- *Harmonic numbers are 14 for Ring 1, and 16 for Ring 2*
- *High Q_s values are favoured for accurate rf beam steering*
- *Frequency range for H^- ions in Ring 1: 9.933 to 59.27 MHz*
- *Frequency range for $C4^+$ in Ring 1: 9.9331 to 24.254 MHz*
- *Frequency range for $C4^+$ in Ring 2: 24.254 to 68.655 MHz*
- *Ring 1 has two straights for rf cavities and Ring 2 has four*
- *Broad band, 115°, 1 m drift tubes in ring 1 (~ 1.5 kV / turn)*
- *Ferrite tuned drift tubes proposed for Ring 2 (~ 5 kV / turn)*