Recent Developments in Our Hadron Therapy Complex

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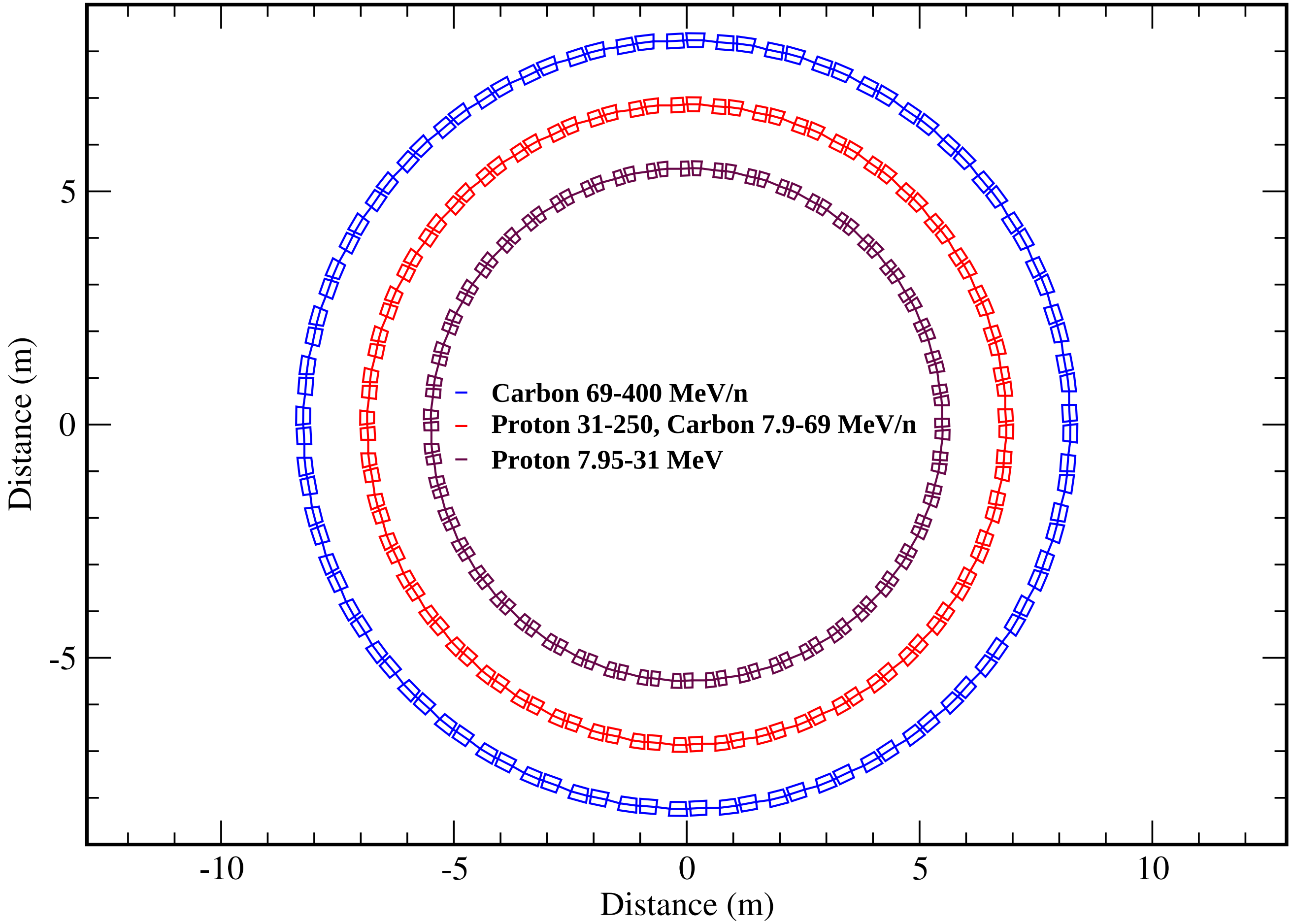
http://keil.home.cern.ch/keil/Conferences/Apr07FFAG/talk.pdf

Schematic layout of the rings



Alternative layout with rings on either side of straight beam line

Beam Parameters of H^+ and C^{6+} in rings 1, 2, 3

Particle	H^+			
Ring	1-Inj	1-Extr	2-Inj	2-Extr
Kin. En.(MeV)	7.951	30.97	30.97	**250**
β	**0.1294**	0.2508	0.2508	0.6136
$B\rho$(Tm)	0.4083	0.8107	0.8107	**2.432**
$\delta p/p$	-0.3301	$+0.3301$	$\mathbf{-0.5}$	$\mathbf{+0.5}$

Particle	C^{6+}			
Ring	2-Inj	2-Extr	3-Inj	3-Extr
Kin. En./u(MeV)	7.8934	68.801	68.801	**400**
β	**0.1294**	0.3645	0.3645	0.7145
$B\rho$(Tm)	0.8107	**2.432**	2.432	6.3472
$\delta p/p$	$\mathbf{-0.5}$	$\mathbf{+0.5}$	-0.4459	$+0.4459$

Design parameters max. kinetic energies, β at injection, momentum ranges and rigidities $B\rho$ in **bold** font

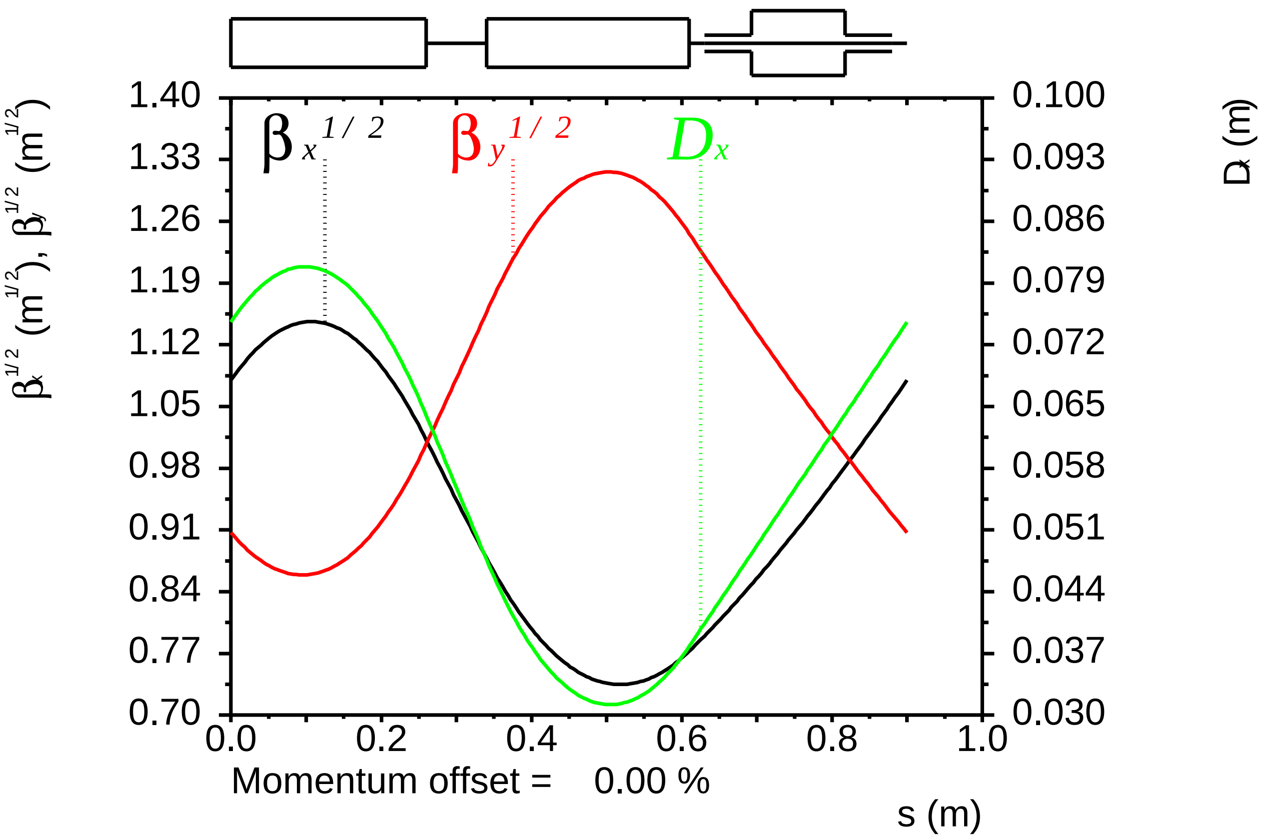
Discussion of Design Choices

- Ring 1 only for H^+, Ring 2 for both H^+ and C^{6+}, Ring 3 only for C^{6+}
- Maximum kinetic energies fixed at 250 MeV for H^+ and 400 MeV/u for C^{6+}
- Ring 2 accelerates by a factor 3 in momentum and is the most difficult one
- Rings 1 and 3 accelerate by smaller factors
- H^+ and C^{6+} have equal rigidities $B\rho$ in Ring 2
  $\Rightarrow$ equal magnet excitation for H^+ and C^{6+}
- H^+ and C^{6+} have equal β at injection into Ring 1 and Ring 2, respectively
  $\Rightarrow$ equal RFQ and linac for H^+ and C^{6+}
- Circumferences in the ratio 4:5:6 useful for RF system
- All other relativistic beam parameters follow from the design parameters

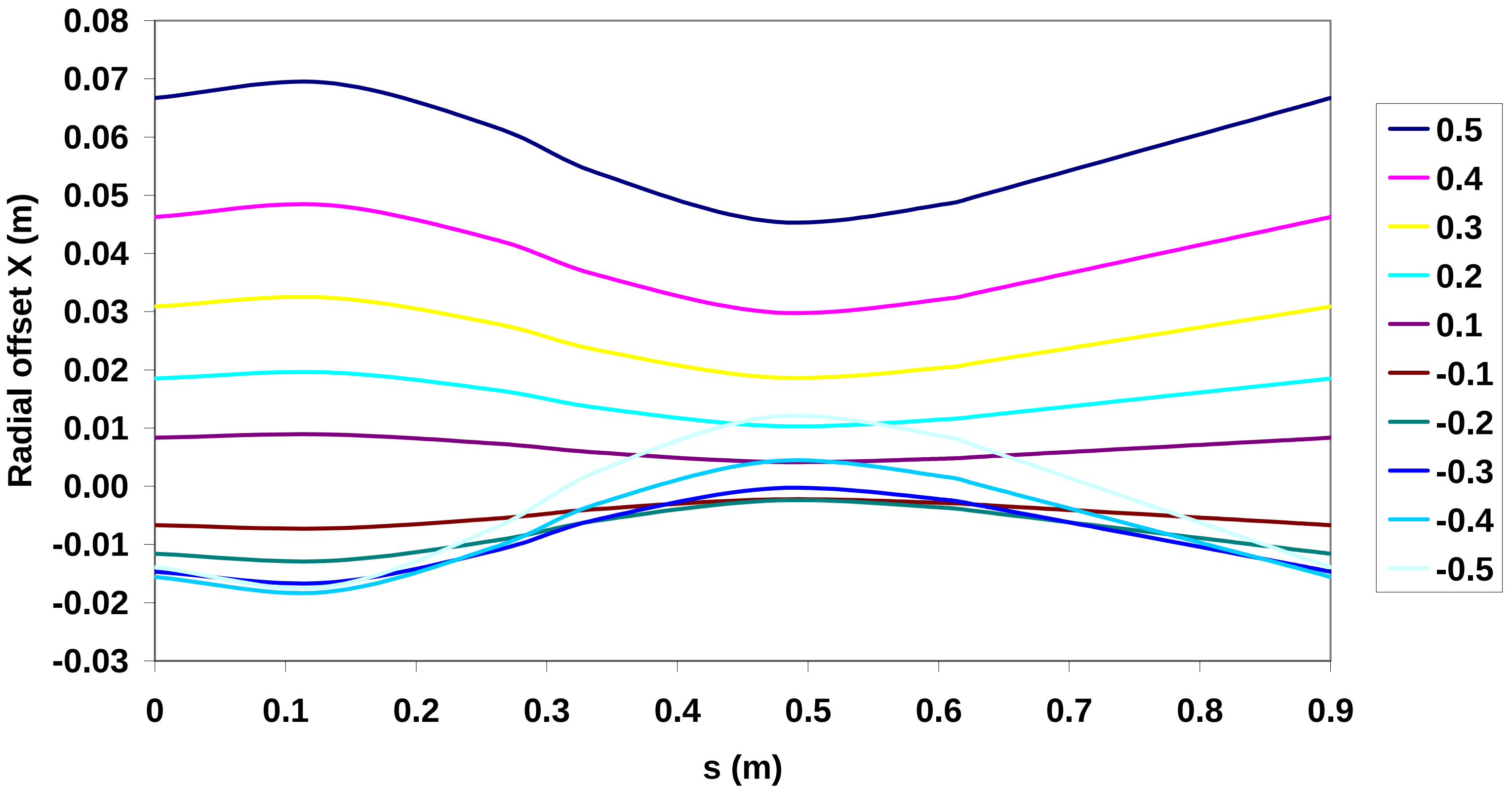
Lattice Issues

- All 3 rings have 48 cells
- All magnets are combined-function dipoles
- All F magnets bend away from the ring centre
- Path length varies like $(\Delta p/p)^2$ near reference momentum
  $\Rightarrow$ mimimal radial spread of off-momentum orbits
  $\Rightarrow$ minimal radial aperture
- Present examples from Ring 2

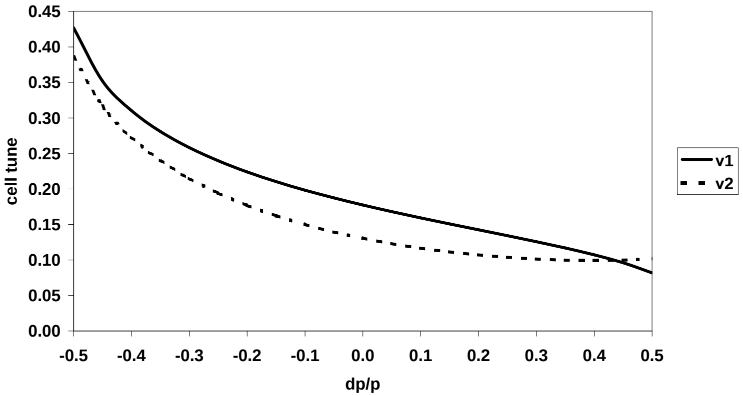
Orbit Functions of Ring 2

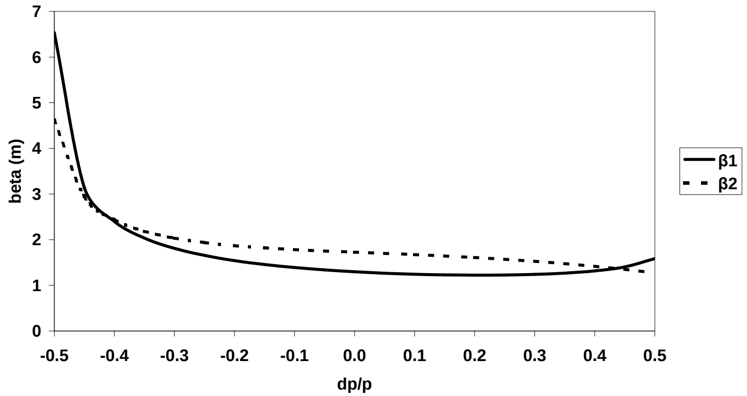


Horizontal orbit offset X in m along a cell of Ring 2



Cell Tunes and β-functions vs. $\delta p/p$





- Keep cell tunes away from 0.5 for $\delta p/p \to -0.5$ and away from 0 for $\delta p/p \to +0.5$
- Avoid steep increases of β-functions for $\delta p/p \to \pm 0.5$
- Play with shape of dipoles and values of ν_1 and ν_2 at $\delta p/p = 0$

RF System Parameters I

- Abandoned harmonic number jumping
  - Large circumferential acceleration ΔE, in particular in Ring 3
  - High frequency at about 1.3 GHz hardly compatible with aperture
  - Conclude that HNJ is unsuitable for rings with small circumference C
- Adopted frequency modulated systems
  - Broad-band transmitters
  - Frequencies between 8 and 25 MHz
  - Relative rate of frequency change at injection too high for ferrites

$$\frac{1}{f_i}\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{c\Delta E}{CE_0\beta_i\gamma_i^3}$$

    with rest energy E_0 and relativistic parameters β_i and γ_i
  - Low-Q RF cavities
  - Modern permeable materials from various suppliers
- Fall-back solution with just one bunch has even lower RF frequencies

RF System Parameters II

Ring	Ion	h	f_i(MHz)	f_f(MHz)	N	T (ms)
1	H^+	8	8.977	17.40	1500	0.9063
2	H^+	5	**8.701**	21.29	3000	0.9594
2	C^{6+}	10	8.977	**25.29**	1500	0.8625
3	C^{6+}	6	12.65	24.79	3000	0.9192

- Low harmonic numbers h explain ratio 4:5:6 of circumferences C
- Transfer bunch trains into buckets
- Fill only every second bucket with H^+ in Ring 1, and with C^{6+} in Ring 2
- RF systems in all 3 rings have similar frequency ranges
- Keep acceleration time T below 1 ms at constant ΔE

$$T = \frac{CN(\beta_f\gamma_f - \beta_i\gamma_i)}{c(\gamma_f - \gamma_i)}$$

with number of turns N and final relativistic β_f and γ_f

RF System Parameters III

Ring	Ion	$\frac{\mathrm{d}f/\mathrm{d}t}{f_i}$(1/ms)	ΔE(kV/u)	$10^3\Delta p/p$	A(meVs)	$10^3 Q_s$
1	H^+	1.061	15.23	3.800	9.400	5.720
2	H^+	1.939	72.48	5.110	52.88	6.749
2	C^{6+}	2.280	40.61	4.119	161.5	9.374
3	C^{6+}	1.519	110.4	5.100	758.7	7.887

- Relative rate of frequency change $\frac{\mathrm{d}f/\mathrm{d}t}{f_i}$ is highest and tabulated at injection
- Circumferential acceleration ΔE is constant
- Stable phase angle is $\pi/6$ from nearest zero crossing
- Bucket area A is smallest and tabulated at injection
- Half bucket height $\Delta p/p$ and synchrotron tune Q_s are smallest at end of acceleration
- Bunches in trains of $\leq$4 H^+bunches in Rings 1 and 2, $\leq$5 C^{6+}bunches in Rings 2 and 3
- Shorter bunch trains might increase the rise time of the kickers
- Operating all rings with one bunch is an alternative

Magnets

- Table shows apertures and fields of the combined function F and D magnets
- Inner and outer horizontal aperture radius from radial offsets and betatron amplitudes
- Variation of B across horizontal aperture in rows labelled B at inner/outer apert radius
- Fields in F magnets change sign inside aperture, those in D magnets do not

Magnet	F			D		
Ring	1	2	3	1	2	3
Inner hor apert radius	-27	-40	-32	-10	-13	-12
Outer hor apert radius	28	76	73	19	59	56
B at inner apert radius	-0.68	-1.40	-2.40	0.82	1.69	3.34
B at outer apert radius	0.17	0.57	0.81	0.44	0.50	1.30
Vert half apert	8	13	7	15	21	11

- Conventional iron-dominated magnets in Rings 1 and 2, excited by resistive room-temperature coils, or by coils of high-temperature superconductor
- Maximum B in Ring 3 in range of easy superconducting magnets

Injection and Extraction

- Extraction in two stages
  - Full-aperture fast kicker deflects extracted beam such that it is outside circulating beam in phase space
  - Septum magnet deflects the extracted beam, such that it misses components downstream, and sends it into a transfer line
- Energy of extracted beam varied by changing number of turns
- Injection uses similar components in reverse order

Ring	1	2	3
Kick angle/mrad	11.5	7.6	4.5
Rise time/ns	120	80	80
Aperture width/mm	52	107	94
Aperture height/mm	28	36	19
Kicker length/m	0.2	0.2	0.2
Kicker field/T	0.047	0.092	0.14

Future Work

- Optimum number of magnets against aperture?
- Circumference ratio 4:5:6 close to optimum?
- Are ratios 3:4:5 or 2:3:4 better?
- Realistic scenarios for injection and extraction?
- Effects of crossing resonances, all driven by field components and harmonics only driven by errors?
- Engineering?
- Cost estimates?