Are FFAG Rings for Hadron Therapy Competitive?

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`http://keil.home.cern.ch/keil/Conferences/08FFAG/compete.pdf`

Introduction

- With A.M. Sessler and D. Trbojevic I published on linear non-scaling FFAG H^+ and C^{6+} rings for hadron therapy
- I stand by all technical statements in our publications
- We identified several remaining technical problems that I will not address today
- Instead, I will show that FFAG H^+ and C^{6+} rings of any style inevitably need large circumferential accelerating voltages and huge, expensive RF systems, contrary to cyclotrons for H^+ and synchrotrons for C^{6+}
- I will also show two examples of such RF systems that we have studied in the past
  - A high-frequency system using harmonic number jumping HNJ
  - A low-frequency system using modern permeable materials

  which indeed need large circumferential accelerating voltages

Energy Gain in FFAG Rings

- In linear non-scaling FFAG rings variation of tunes causes crossing of resonances, all driven by errors, and emittance increase
- I am not aware of quantitative simulations of emittance increase
- In other styles of FFAG rings repetition rate $R \approx 1$ kHz desirable
- Estimates of emittance increase and R limit number of turns at about $N \approx 1000$
- Use parameters of three-ring circus at Cyclotrons 2007
- Assume stable phase angle with $\sin \varphi_s = 0.5$, which may be somewhat pessimistic

Ring	1	2	2	3
Particle	H^+	H^+	C^{6+}	C^{6+}
Injection energy E_i/MeV/n	7.951	30.97	7.893	68.80
Extraction energy E_f/MeV/n	30.97	250	68.80	400
Energy gain/turn ΔE/keV/n	23.02	219.0	60.9	331.2
Peak circumferential acceleration U/kV	46	438	244	1325

- ΔE and U both proportional to $1/N$
- Independent of frequency f_{RF}, and style of RF system and FFAG ring

RF Systems Using HNJ

- With rest energy E_0, harmonic number h and relativistic parameters β and γ

$$\Delta E = -E_0 \beta^2 \gamma^3 \Delta h / h$$

  find that $\Delta E \propto 1/h$, and large h is desirable, limited only by diameter of beam ports

- RF system parameters at $f_{\rm RF} \approx 1.3$ GHz, initial and final harmonic numbers h_i and h_f, initial step $|\Delta h|$, number of turns, maximum peak circumferential acceleration U

Ring	Ion	h_i	h_f	$\|\Delta h\|$	turns	U (MV)
1	H^+	1158	597	7	272	0.11
2	H^+	797	325	25	123	2.2
2	C^{6+}	1544	548	26	274	0.56
3	C^{6+}	685	349	17	105	7.9

- ILC/EMMA cavities have 70/40 mm beam ports, smaller than aperture needed
- Even larger circumferential acceleration U than on previous page
- Fewer turns than assumed in resonance calculation
- HNJ might work for H^+ in Ring 1 and C^{6+} in Ring 2

Frequency Modulated RF Systems

Broad-band transmitters at frequencies between 6.5 and 19 MHz feed low-Q RF cavities filled with modern permeable materials from various suppliers

Ring	Ion	h	f_i(MHz)	f_f(MHz)	N	T (ms)	ΔE(keV/u)
1	H^+	6	6.733	13.05	1500	0.9063	15.34
2	H^+	4	**6.526**	15.97	3000	1.023	73.01
2	C^{6+}	8	6.733	**18.97**	1500	0.9200	40.61
3	C^{6+}	5	9.485	18.60	5000	1.702	66.24

- Low harmonic numbers h related to ratio 3:4:5 of circumferences C
- Fill every 2nd bucket with H^+ in Ring 1 and C^{6+} in Ring 2
- Violate rules $N \approx 1000$ and acceleration time $T < 1$ ms at constant ΔE

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

  with initial and final relativistic β and γ

- The values of $N\Delta E$ above agree with table on page 3

RF Power Parameters in FM Systems

- Start from LEIR cavities with $R_L = 660\ \Omega$ and double power $W_L = V_L^2/(2R_L)$
- Assume stable phase angle $\pi/4$ from nearest zero crossing
- Adjust number of cavities N such that $V \leq 6$ kV

Ring	Ion	N	V (kV)	W (kW)
LEIR		1	4	12
1	H^+	4	5.4	22.3
2	H^+	18	5.7	24.9
2	C^{6+}	20	5.7	25.0
3	C^{6+}	32	5.9	26.0

- RF system in Ring 1 is easy
- RF system in Ring 2 fills about 40% of available straight sections, needs 0.5 MW
- RF system in Ring 3 fills about 67% of available straight sections, needs 0.83 MW
- You may now understand why we violated the $N \approx 1000$ and $T < 1$ ms rules

Conclusions

- Emittance growth due to resonance crossings, still to be confirmed by detailed multi-particle simulations with errors, and repetition rate $R \approx 1$ kHz impose upper limit on number of turns $N \approx 1000$
- Large energy gain in a turn $\Delta E = (E_f - E_i)/N$ results in large circumferential acceleration U, independent of f_{RF}, and style of RF system and FFAG ring
- Two RF systems considered
  - In HNJ system upper limit on harmonic number h, given by beam port aperture, results in even larger circumferential acceleration U and $N \ll 1000$
  - In low-Q, low-frequency system, limited straight section space and RF power result in $N \gg 1000$
- Advantages of FFAG rings
  - Repetition rates of order 1 kHz
  - Fast ejection
- Do these advantages justify the extra cost of the RF system?