

Ion-pair candidates and design considerations for mixed-beam delivery in NIMMS

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Outline

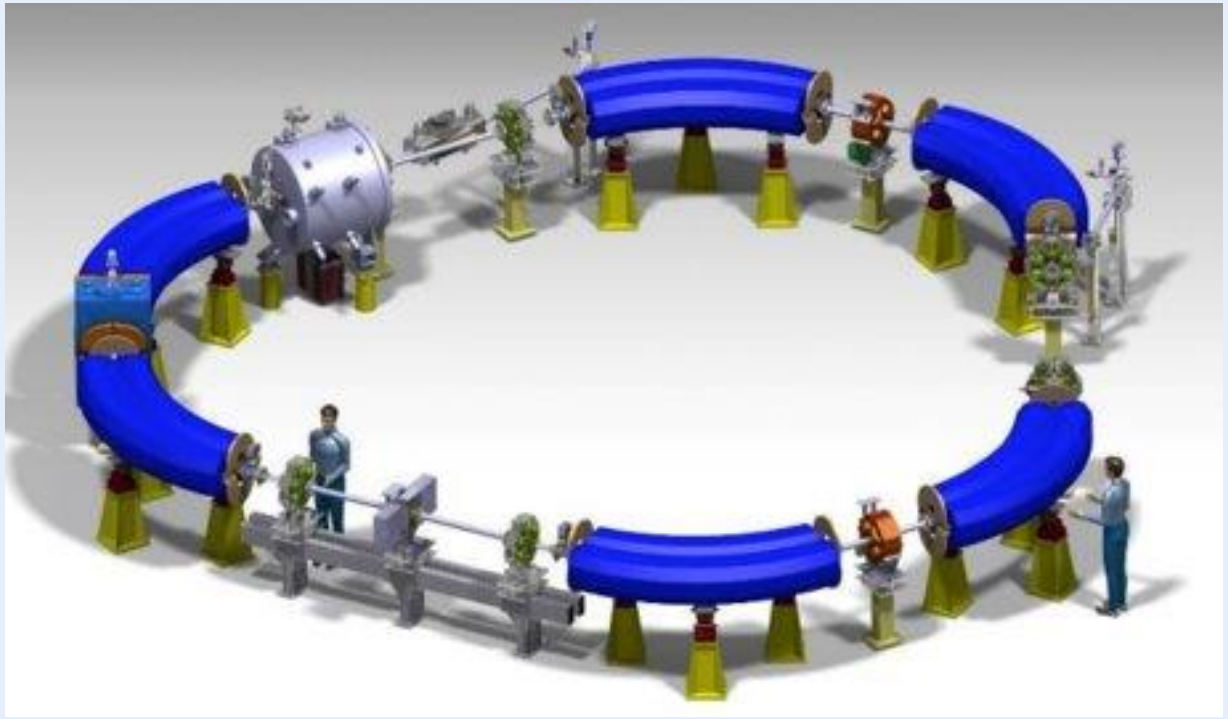
- Introduction to NIMMS collaboration and HeLICS
- Range requirements in medical mixed-beams
- Accelerator considerations for novel facilities
  - Mixed ion beams in HeLICS / C-LICS
- Conclusions

NIMMS - future particle therapy technologies

- Size and cost of the accelerator limiting factor in widespread application of ion therapy

Next Ion Medical Machine Study (NIMMS)

- New facility design for new delivery modalities
- Integrating demands of medical community biological research opportunities



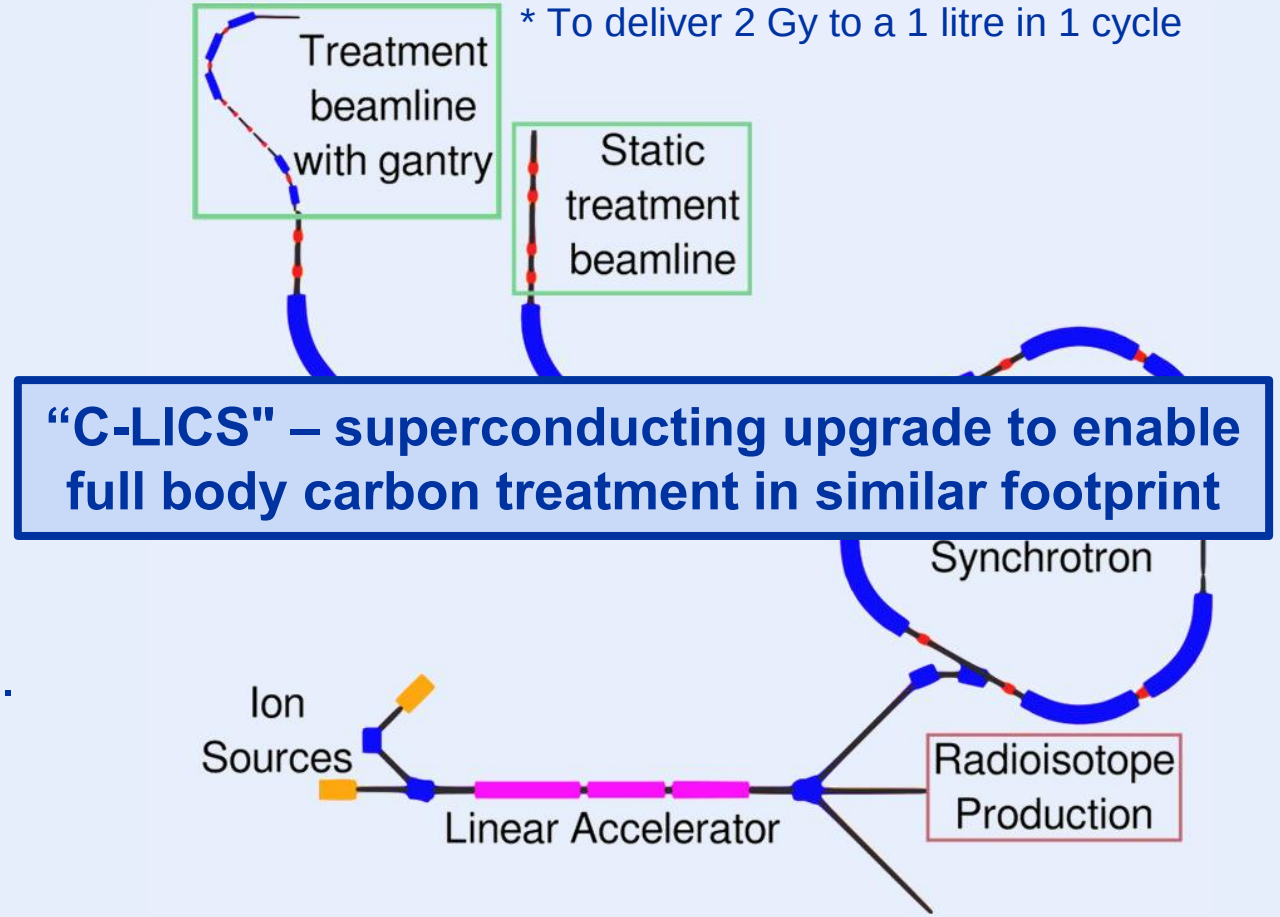
HeLICS synchrotron facility

Helium Light Ion Compact Synchrotron

- Clinical treatment center and scientific research infrastructure
  - **Proton and helium treatment**
  - Research with heavier ions
- Full body proton radiography imaging
- Parallel radioisotope production
- New delivery methods: FLASH, mini beams...
  - **Mixed ion beams!!**

	p^+	$^4He^{2+}$
Intensity*	2.6 e11	8.2 e10
Injection energy (MeV/u)	7-10	5
Treatment energy (Mev/u)	60-220	60-220

* To deliver 2 Gy to a 1 litre in 1 cycle



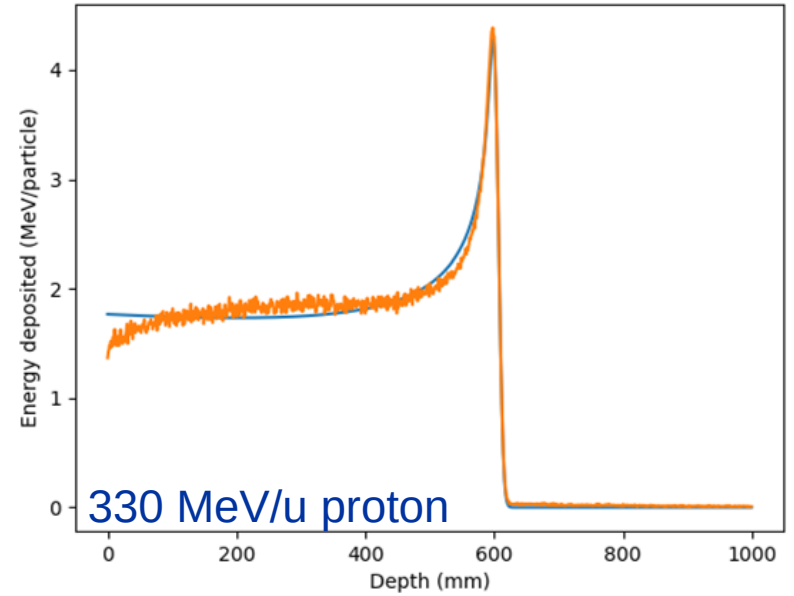
"C-LICS" – superconducting upgrade to enable full body carbon treatment in similar footprint

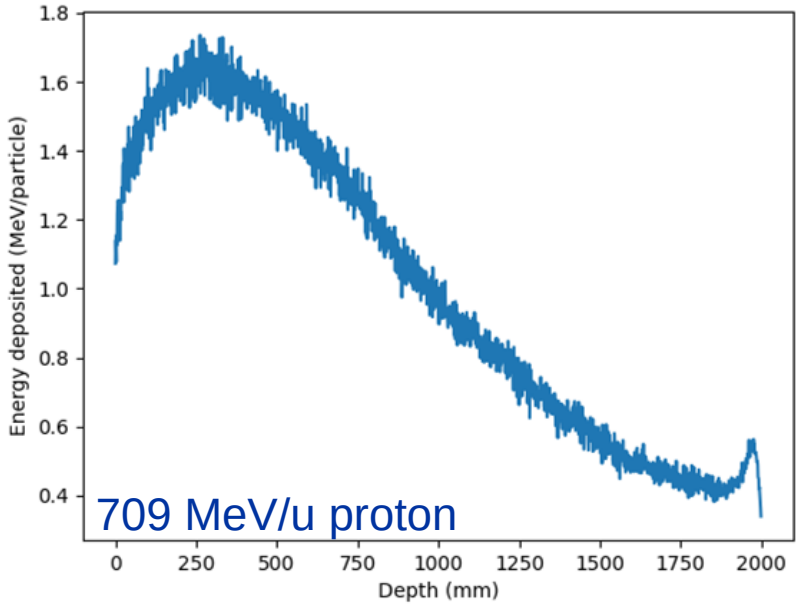
Mixed-beams: range requirements

- Treatment ion to tumour, imaging ion to detector
  - **Simple in theory - not in practice!**
- Physical limitation of deeper imaging ion ranges
  - Less pronounced Bragg peak
  - Increased range straggling, MCS & nuclear interactions
  - Radiation protection concerns

Further restriction from the treatment plan and detection capabilities!

Geant4: Monte Carlo range simulations



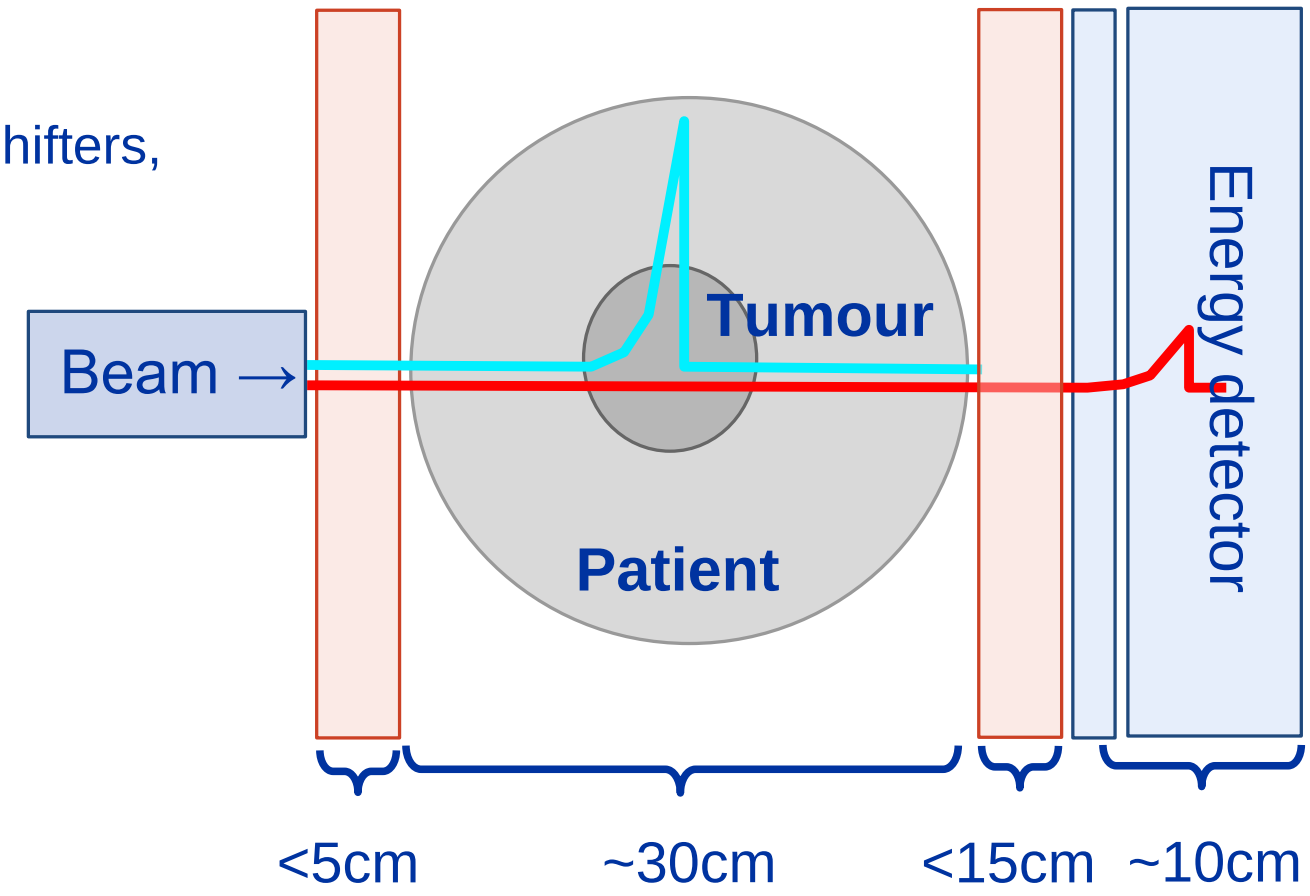


Potential imaging ions

- **Suitable range treatment plan specific!**
  - Tumour location, patient size, range shifters, sensitive area of detector…
  - No universal range limits

Potentially useful range:

- Min: ~180 mm
  - Thickness of adult head
- Max: >600 mm
  - Patient + range shifters + detector
  - For medical / detector physicist to define



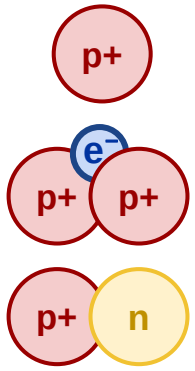
Potential imaging ions

1. Identify limits of potentially useful imaging range ✔

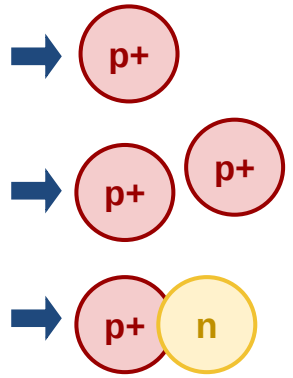
2. Calculate ion energies at specified magnetic rigidities *Bρ = p/q* – charge state matters!

3. Correlate beam energies to range in Geant4 **– fully stripped ions!**

R: Range in water!



Ion	q/A	E(Bρ = 2.3)	R(Bρ =2.3)	E (Bρ = 4.5)	R(Bρ = 4.5)
H^+ (p)	1	220 MeV / u	30 cm	709 MeV / u	~ 2 m!
H_2^+	1/2	60 MeV / u	3 cm	220 MeV / u	30 cm
$^2H^+$ (D)	1/2	60 MeV / u	6 cm	220 MeV / u	60 cm



Potential imaging ions

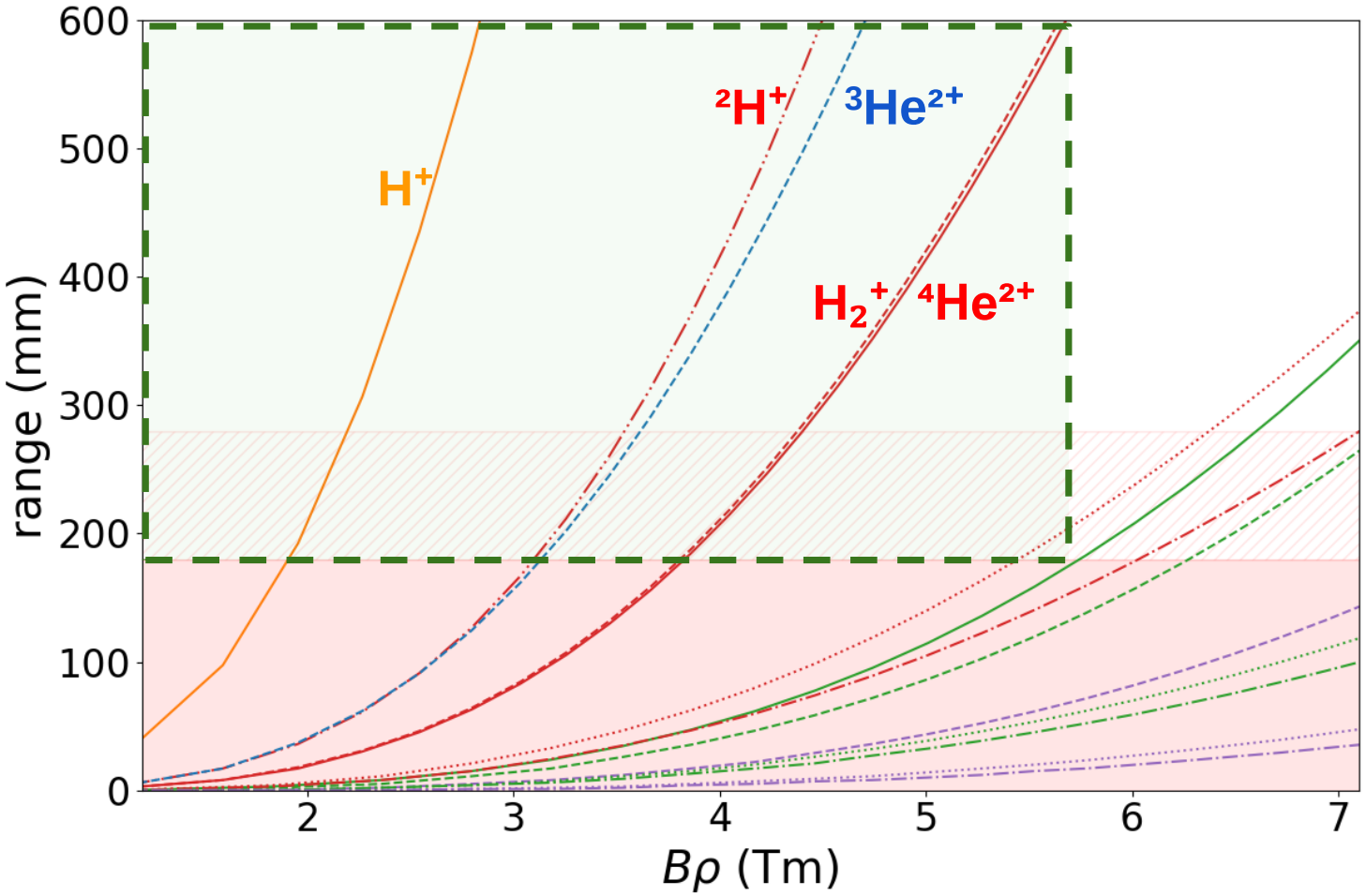
3. Correlate beam energies to range in Geant4 **– fully stripped ions!**

Candidates for imaging:

- Proton: H^+ (p)
- Deuteron: $^2H^+$ (D)
- Molecular hydrogen: H_2^+
- Helium: $^3He^{2+}$, $^4He^{2+}$

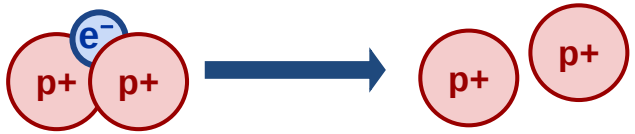
How to combine with treatment ions?

- H^+ / $^4He^{2+}$ / $^{12}C^{6+}$



Proton treatments – imaging ion pairs?

Treatment protons accelerated as H_2^+



Imaging candidates:

H^+ (p): 2 - 7 cm treatment depths

- Lowest imaging dose

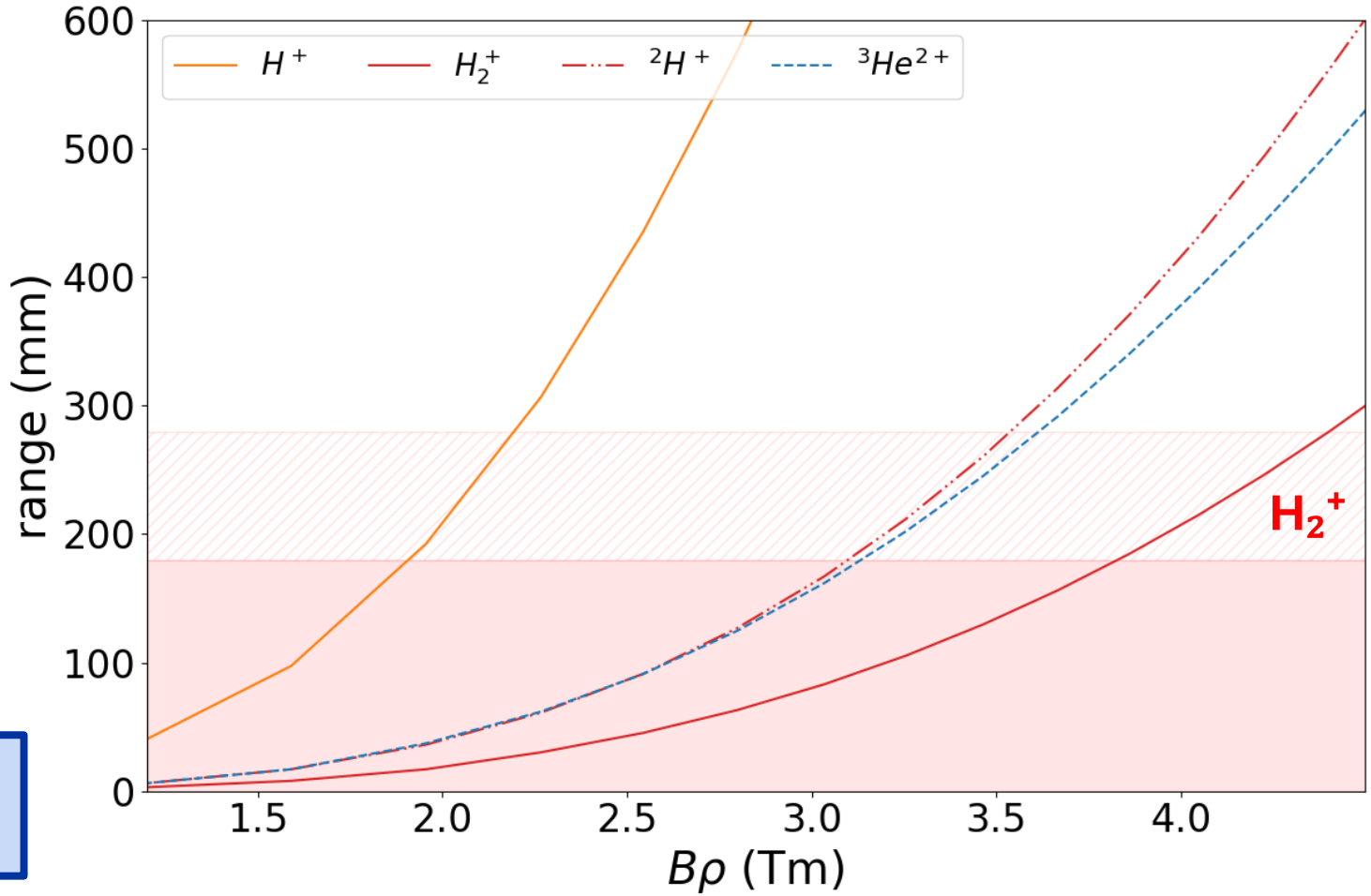
$^2H^+$ (D): 9 - 30 cm treatment depths

- Optimal range difference

$^3He^{2+}$: 9 - 35 cm treatment depths

- Relatively higher imaging dose

Upper range could be extended!



Potential ion pairs

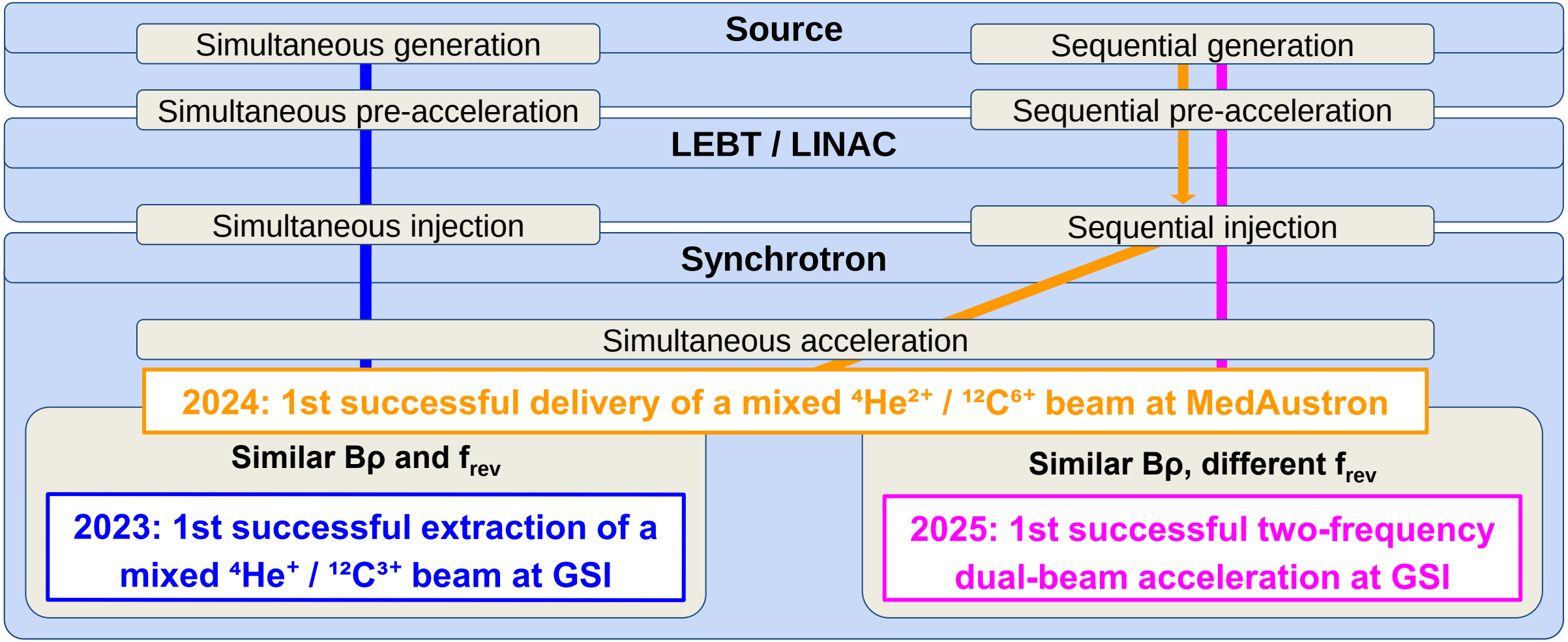
Goal: identify best imaging ion for each treatment species

Treatment ion	q/A	Imaging ion	q/A	Treatment range
H_2^+	1/2	H^+	1	2 - 7 cm ✓
		$^2H^+$	1/2	9 - 30 cm ✓
		$^3He^{2+}$	2/3	9 - 35 cm ✓
$^4He^{2+}$	1/2	H^+	1	2 - 7 cm ✓
		$^2H^+$	1/2	9 - 30 cm ✓
		$^3He^{2+}$	2/3	9 - 35 cm ✓
$^{12}C^{6+}$	1/2	$^2H^+$	1/2	3 - 10 cm ✓
		H_2^+	1/2	6 - 20 cm ✓
		$^3He^{2+}$	2/3	3 - 12 cm ✓
		$^4He^{2+}$	1/2	6 - 20 cm ✓

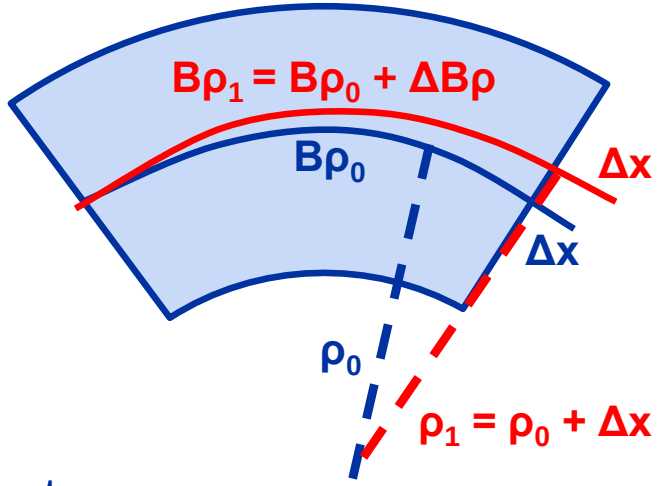
Relatively low imaging ranges might have limited applicability

Mixed ion beam - generation & acceleration

Three (1, 2, 3) paths from source to patient:



Mixed ion beams in HeLICS synchrotron



Similar Bρ and f_{rev}: Single-harmonic RF system

- Small offsets in Bρ allowed
  - Limit defined by mass difference

$$\chi_{sp} = \frac{q_{II}/m_{II}}{q_I/m_I}$$

- Require total effective rigidity offset $\delta_{sp,eff}$ within momentum acceptance

$$\delta_{sp} = \frac{\gamma_I^2}{\gamma_{tr}^2 - \gamma_I^2}\left(\frac{1}{\chi_{sp}} - 1\right)$$

$$\delta_{eff,sp} \approx \frac{1}{\chi_{sp}} - 1 + \delta_{sp}$$

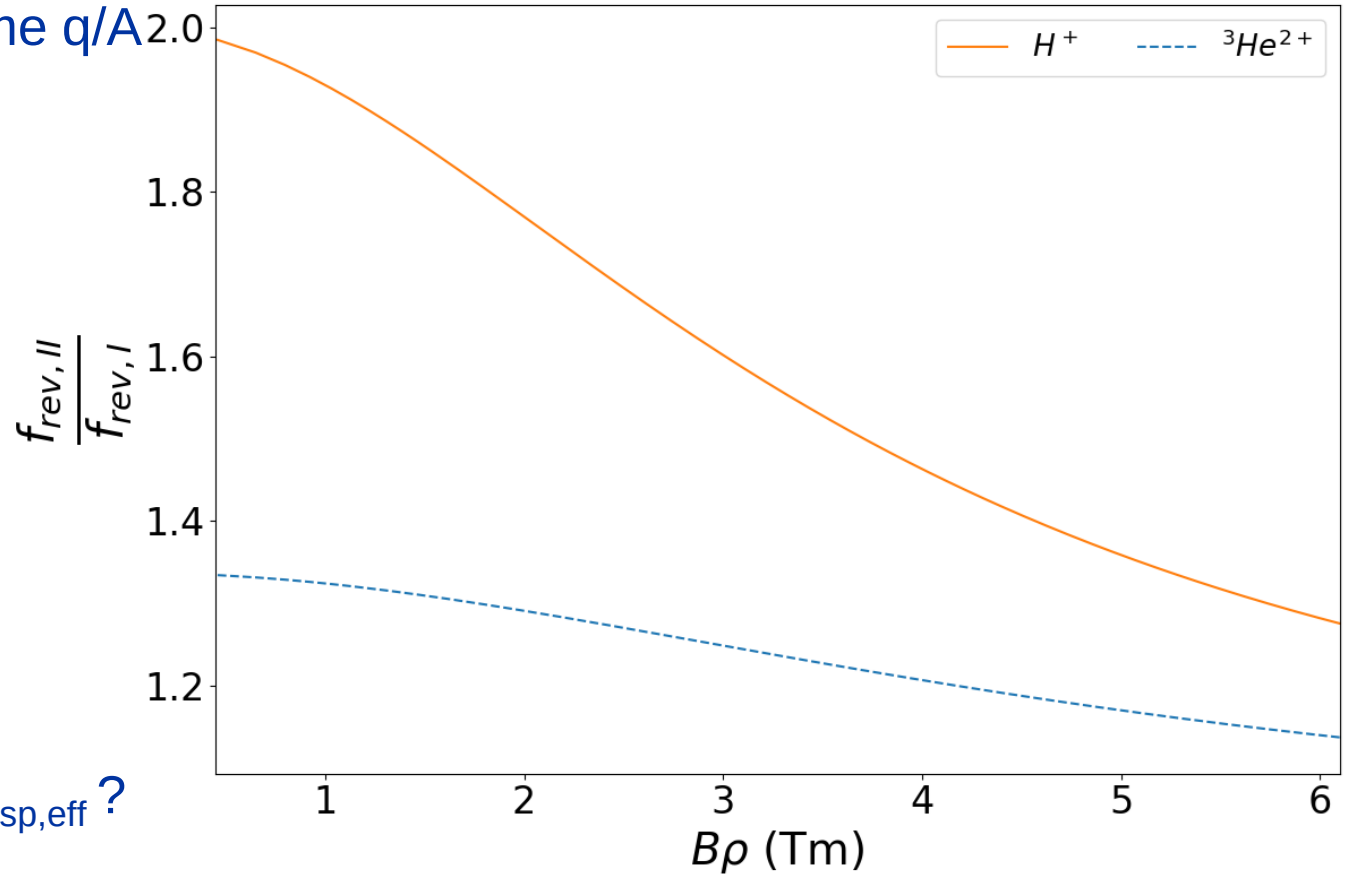
- Effects on dispersion, chromaticity, slow extraction, ..?

Treatment ion	Imaging ion	χ_{sp}	δ_{sp}	$\delta_{sp,eff}$
H_2^+	$^2H^+$	1.00076	-0.12‰	0.88‰
$^4He^{2+}$	$^2H^+$	0.99364	1.00‰	7.40‰
$^{12}C^{6+}$	$^2H^+$	0.99300	1.64‰	8.69‰
	H_2^+	0.99223	1.82‰	9.64‰
	$^4He^{2+}$	0.99935	0.15‰	0.80‰

Mixed ion beams in HeLICS synchrotron

Similar Bρ, different f_{rev}: Independent RF frequencies

- Treatment ions (H_2^+, $^4He^{2+}$, $^{12}C^{6+}$) have same q/A
  - **Nearly identical f_{rev}**
- Two imaging ion options with differing q/A
  - H^+ and $^3He^{2+}$
- Issues from net voltage of 'foreign' RF?
- Simulations foreseen for HeLICS
- What about same q/A particles with large $\delta_{sp,eff}$?



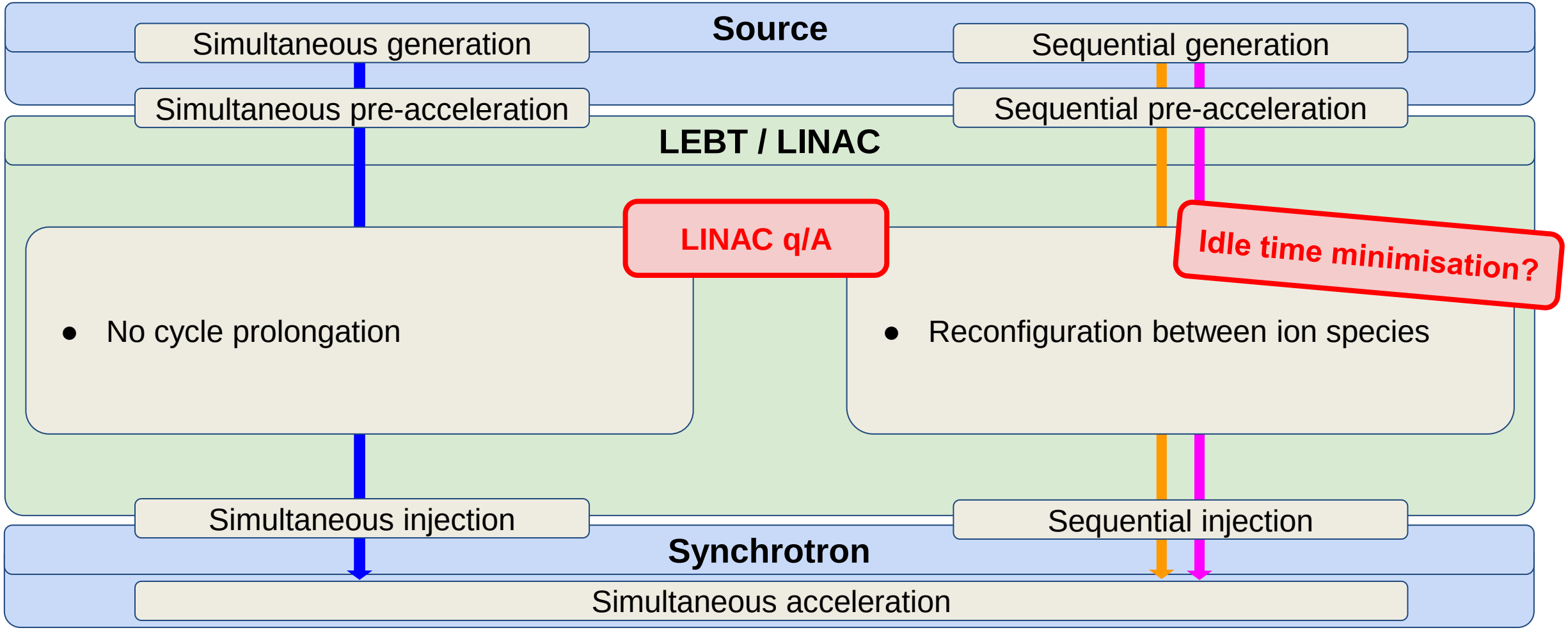
Potential ion pairs

					Synchrotron RF	
Treatment ion	**q/A**	**Imaging ion**	**q/A**	**Treatment range**	**Single**	**Dual**
H_2^+	1/2	H^+	1	2 - 7 cm ✓	✗	✓
		$^2H^+$	1/2	9 - 30 cm ✓	✓	✗
		$^3He^{2+}$	2/3	9 - 35 cm ✓	✗	✓
$^4He^{2+}$	1/2	H^+	1	2 - 7 cm ✓	✗	✓
		$^2H^+$	1/2	9 - 30 cm ✓	✗	✓
		$^3He^{2+}$	2/3	9 - 35 cm ✓	✗	✓
$^{12}C^{6+}$	1/2	$^2H^+$	1/2	3 - 10 cm ✓	✗	✓
		H_2^+	1/2	6 - 20 cm ✓	✗	✓
		$^3He^{2+}$	2/3	3 - 12 cm ✓	✗	✓
		$^4He^{2+}$	1/2	6 - 20 cm ✓	✓	✗

How close can Δ(q/m) be for dual frequency acceleration?

Mixed ion beam - generation & acceleration

Three (1, 2, 3) paths from source to patient:



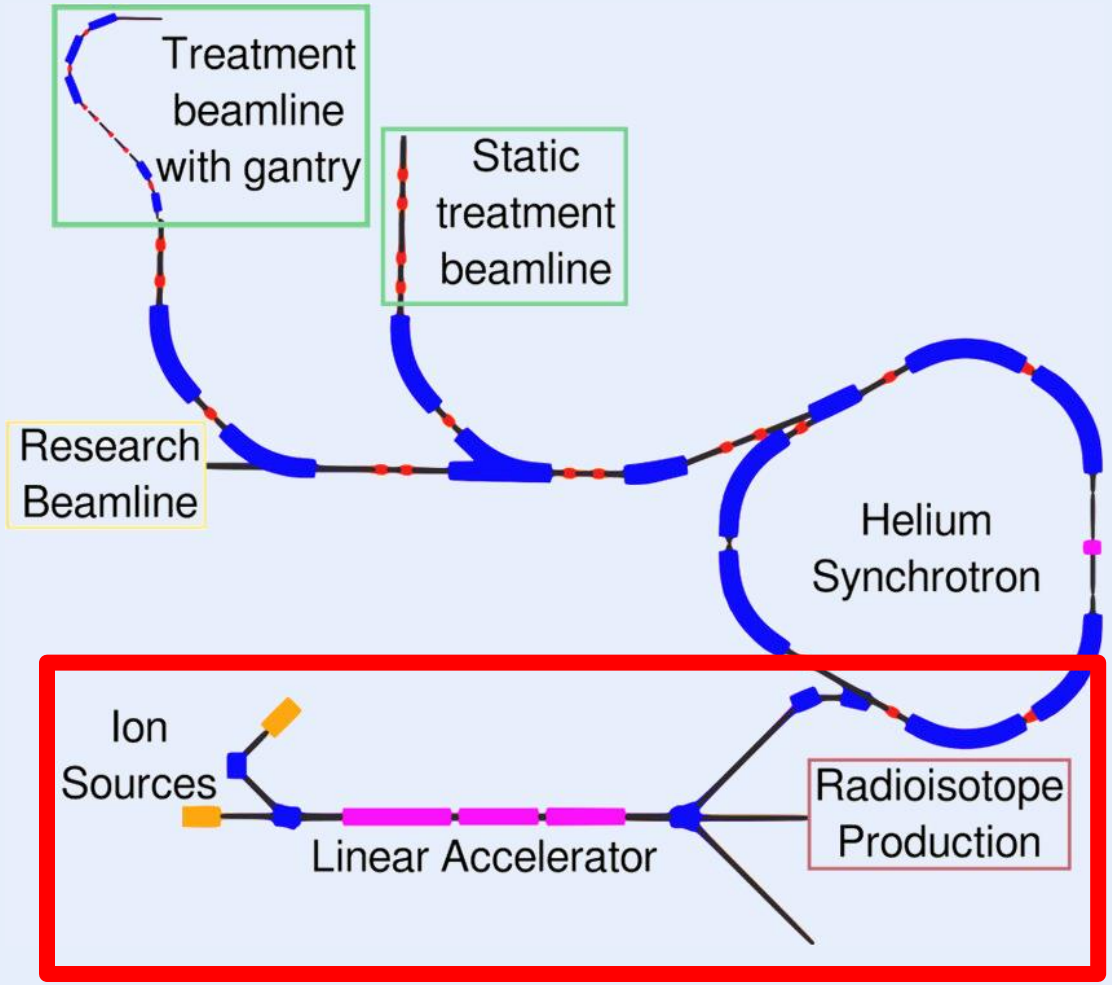
Mixed ion beams in HeLICS injector

LINAC q/A

- HeLICS LINAC: q/A > 1/2
- SC design (C-LICS) LINAC: q/A > 1/3

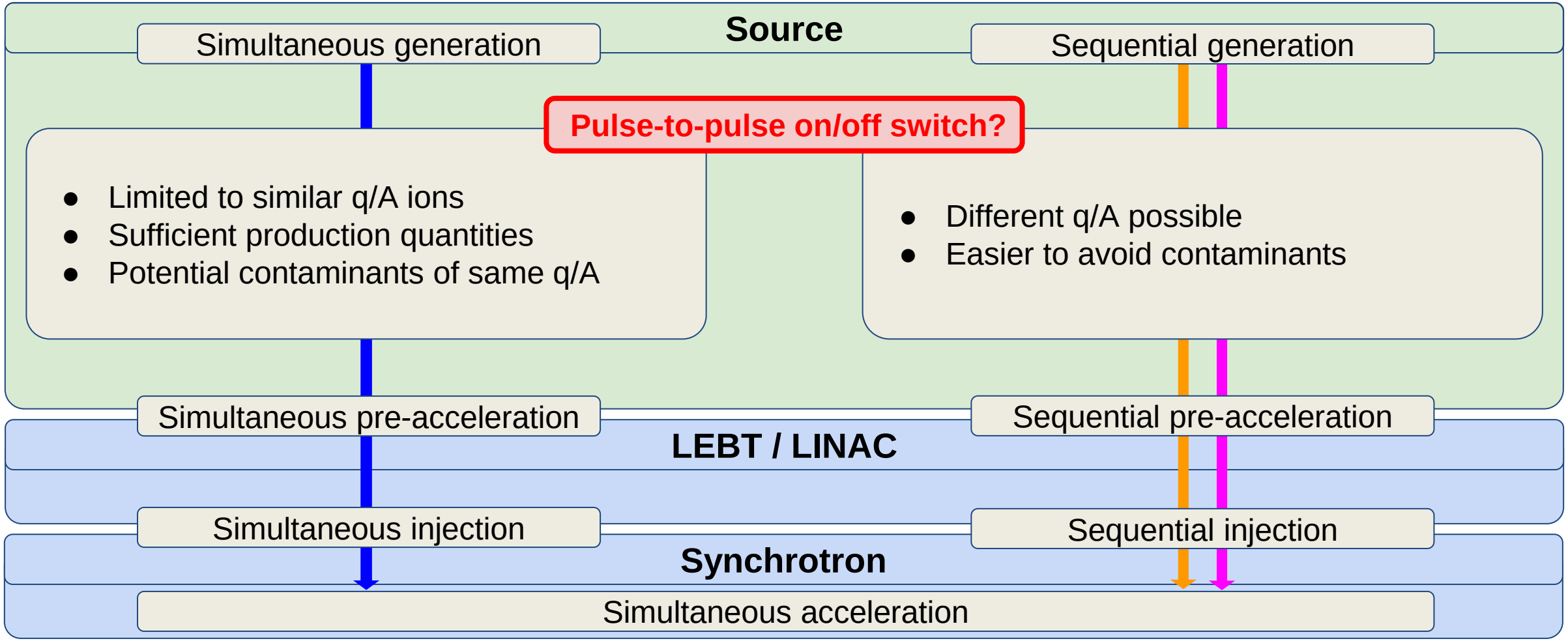
Idle time minimisation?

- For parallel radioisotope production
  - LINAC operation up to 50 Hz
  - Pulse-by-pulse switching of the beam destination
- **Fast reconfiguration for sequential injections!**



Mixed ion beam - generation & acceleration

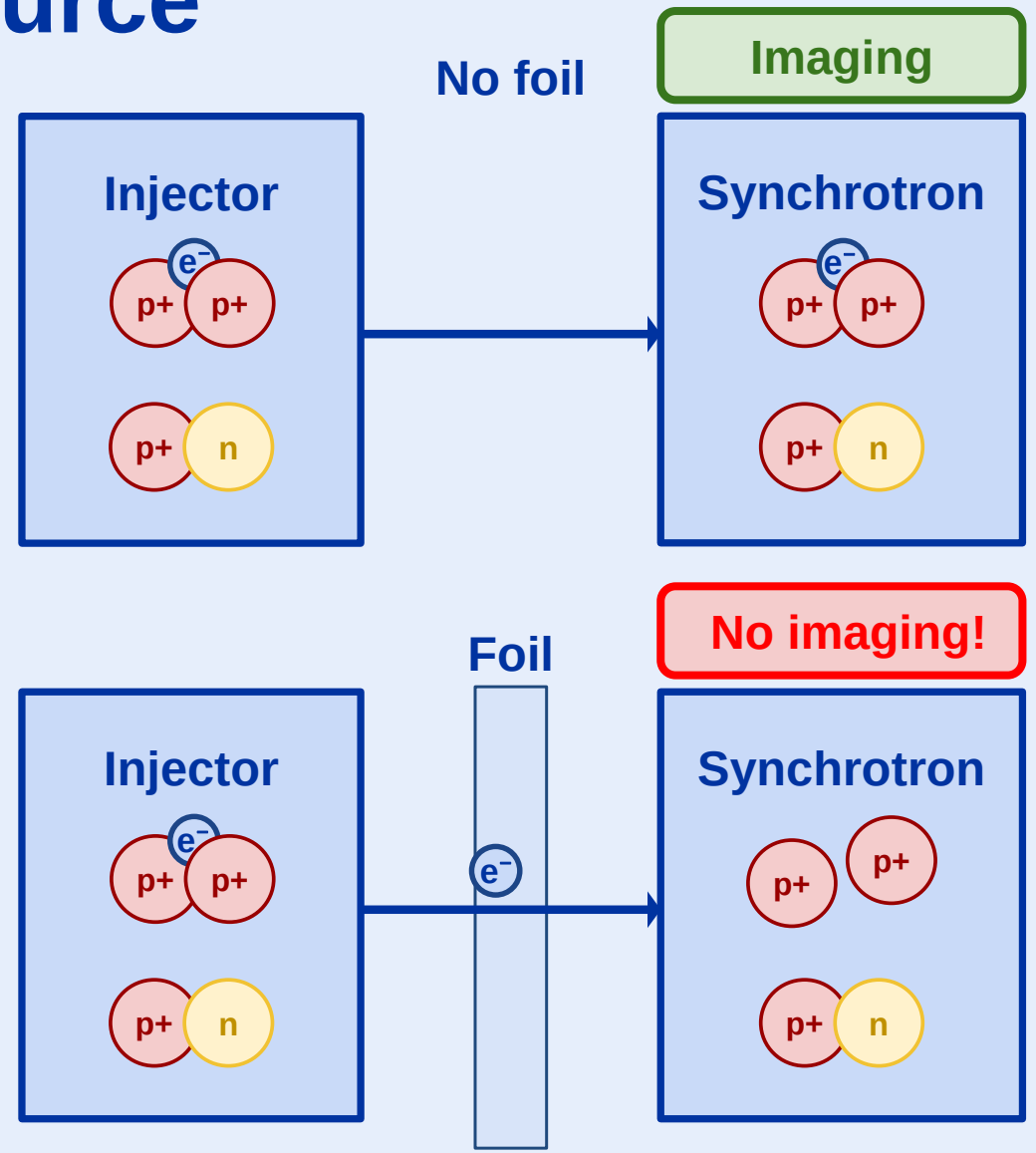
Three (1, 2, 3) paths from source to patient:



Mixed ion beams in HeLICS source

Single ion source pulse-to-pulse on/off switch

- Could be possible for specific ion pairs!
- Fast switching stripping foil after LINAC
  - Modify q/A of particles going to synchrotron
- Loss of imaging beam at low energy in synchrotron
  - Collimators to protect the machine?



Sequential or simultaneous injection?

Contamination?

Treatment ion	q/A	Imaging ion	q/A	Sequential	Simultaneous
H_2^+	1/2	H^+	1	✓	✗
		$^2H^+$	1/2	✓	✓
		$^3He^{2+}$	2/3	✓	✗
$^4He^{2+}$	1/2	H^+	1	✓	✗
		$^3He^{2+}$	2/3	✓	✗
$^{12}C^{6+}$	1/2	$^3He^{2+}$	2/3	✓	✗
		$^4He^{2+}$	1/2	✓	✓

Potential ion pairs

					Synchrotron RF		Injection	
Treatment ion	**q/A**	**Imaging ion**	**q/A**	**Treatment range**	**Single**	**Dual**	**Sequential**	**Simultaneous**
H_2^+	1/2	H^+	1	2 - 7 cm ✓	✗	✓	✓	✗
		$^2H^+$	1/2	9 - 30 cm ✓	✓	✗	✓	✓
		$^3He^{2+}$	2/3	9 - 35 cm ✓	✗	✓	✓	✗
$^4He^{2+}$	1/2	H^+	1	2 - 7 cm ✓	✗	✓	✓	✗
		$^2H^+$	1/2	9 - 30 cm ✓	✗	✓	-	-
		$^3He^{2+}$	2/3	9 - 35 cm ✓	✗	✓	✓	✗
$^{12}C^{6+}$	1/2	$^2H^+$	1/2	3 - 10 cm ✓	✗	✓	-	-
		H_2^+	1/2	6 - 20 cm ✓	✗	✓	-	-
		$^3He^{2+}$	2/3	3 - 12 cm ✓	✗	✓	✓	✗
		$^4He^{2+}$	1/2	6 - 20 cm ✓	✓	✗	✓	✓

Conclusions

- Mixed-beams are an interesting design challenge for novel facilities such as HeLICS
- Potential imaging ions of interest: H^+, $^2H^+$, $^4He^{2+}$, $^3He^+$

Endless opportunities to further research!

- Dual frequency acceleration simulations in HeLICS
- Simulations of injector Δ(q/A) limit
- Simultaneous generation: (H_2^+ + $^2H^+$), (H_2^+ + $^4He^{2+}$), ($^3He^+$ / $^{12}C^{4+}$), ($^4He^{2+}$ / $^{12}C^{6+}$)
- More exotic treatment ions: $^2H^+$ / Li / Be / B

Thank you!







Helium treatments – imaging ion pairs?

$^4He^{2+}$ has practically identical range and acceleration to H_2^+

Imaging candidates:

H^+ (p): 2 - 7 cm treatment depths

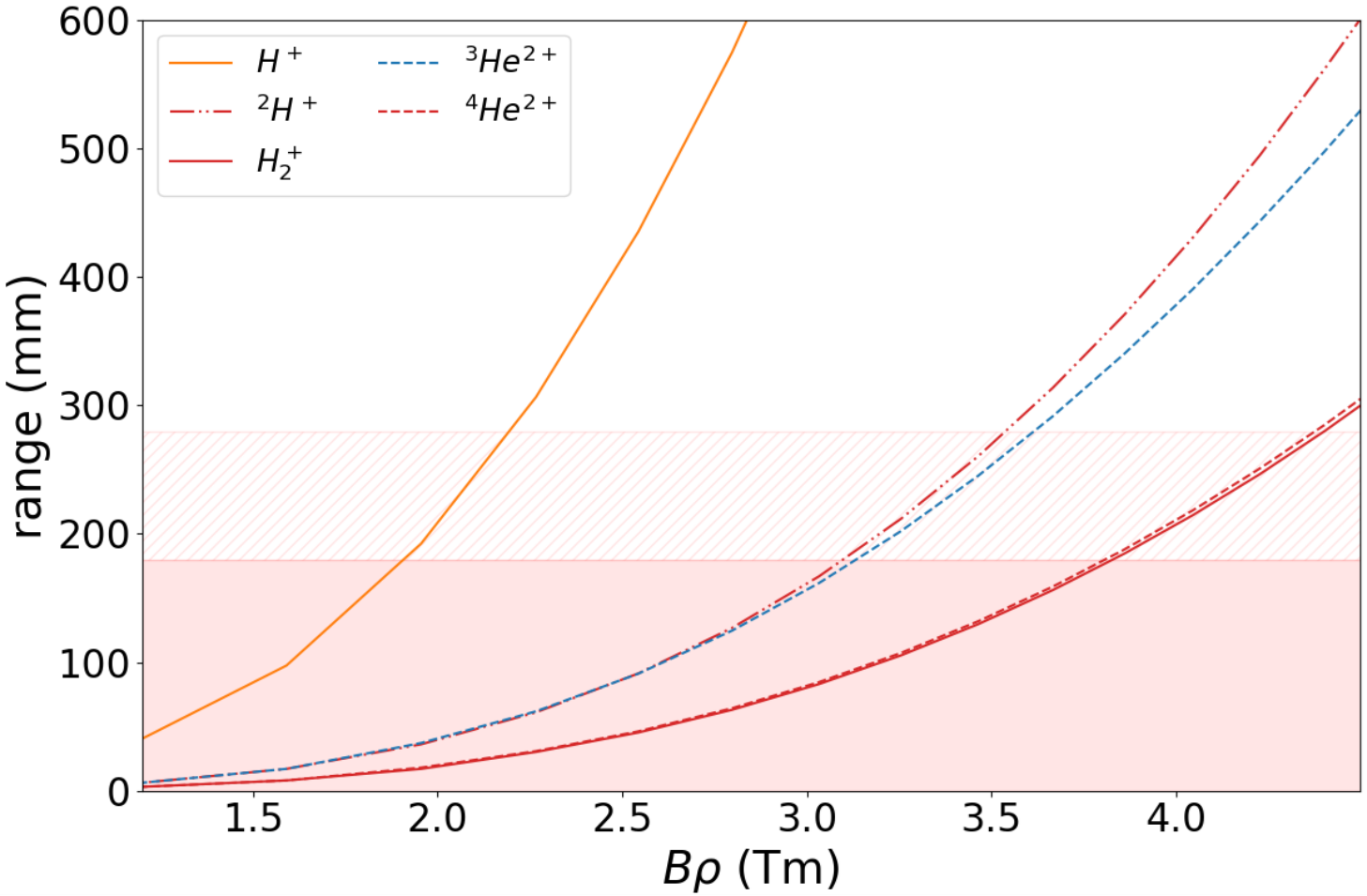
- lowest imaging dose

$^2H^+$ (D): 9 - 30 cm treatment depths

- most optimal range difference

$^3He^{2+}$: 9 - 35 cm treatment depths

- relatively higher imaging dose



Carbon treatments – imaging ion pairs?

Imaging candidates:

$^{2}H^{+}$ (D): 3 - 10 cm treatment depths

- Least favorable range difference

H_2^{+}: 6 - 20 cm treatment depths

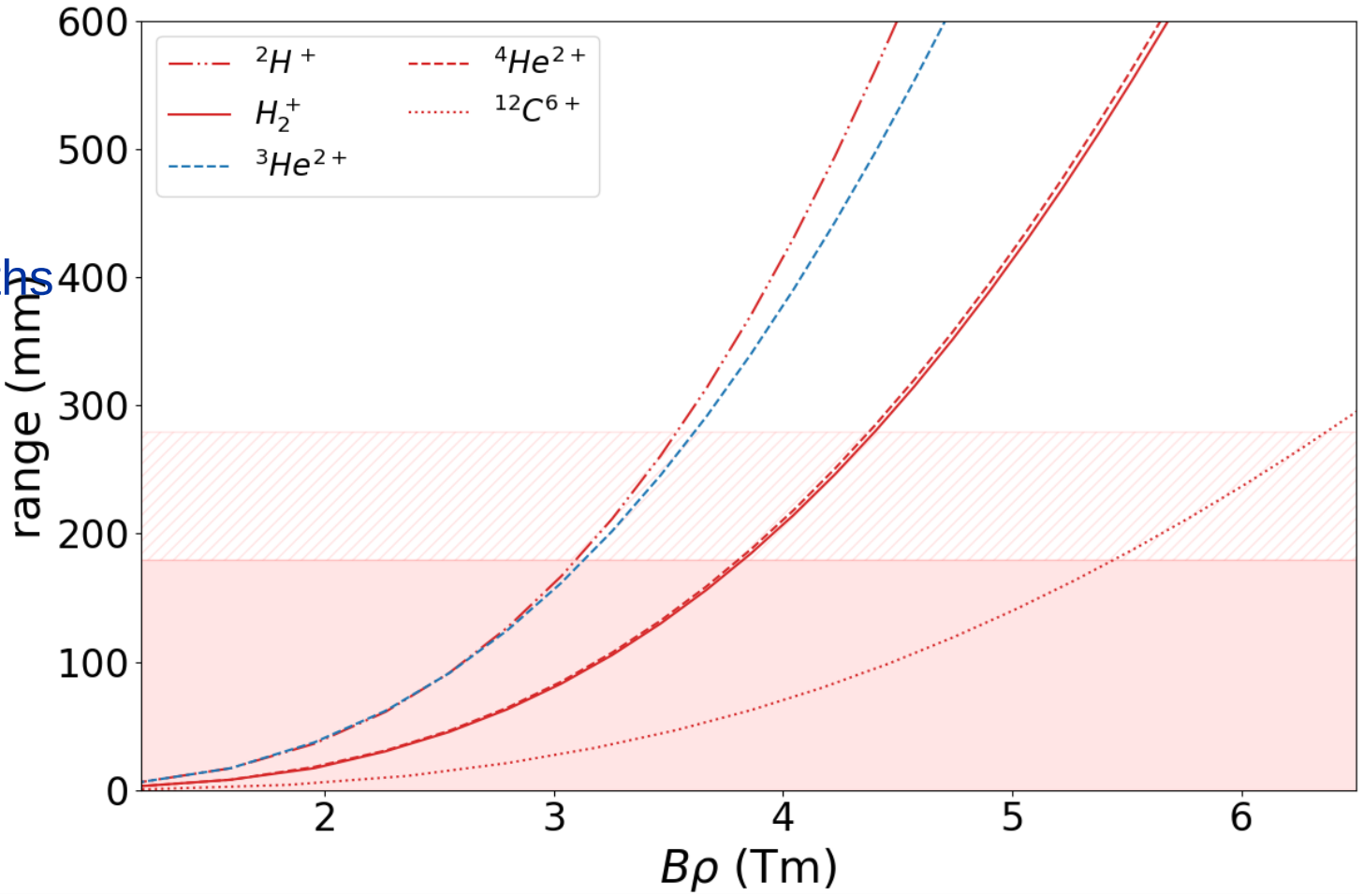
- Lowest imaging dose

$^{3}He^{2+}$: 3 - 12 cm treatment depths

- Shallow tumour imaging

$^{4}He^{2+}$: 6 - 20 cm treatment depths

- **Demonstrated feasibility**



Considered source options for HeLICS:

- PK supernanogun:
  - 14 GHz ECRIS
  - Standard solution for hadron-therapy
- PK-ISIS:
  - 18 GHz ECRIS
- Advanced Ion Source for Hadrontherapy (AISHa)
  - 18 GHz ECRIS

HeLICS source target ion yields

3 ion sources:

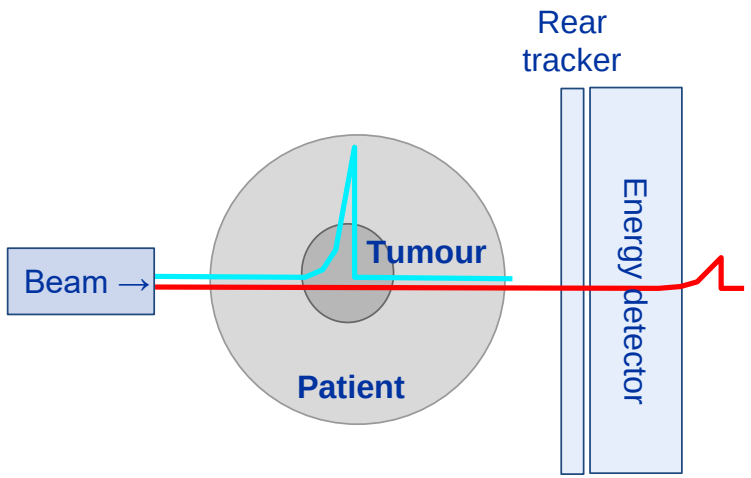
- $^{12}C^{4+}$, 0.6 mA, 45 kV
  0.25 π mm mrad
- $^{4}He^{2+}$, 0.5 mA,
  0.3 π mm mrad
- H^{+} or $^{2}H^{+}$, 5 mA,
  0.2 - 0.3 πmm mrad

Only SC design (C-LICS)

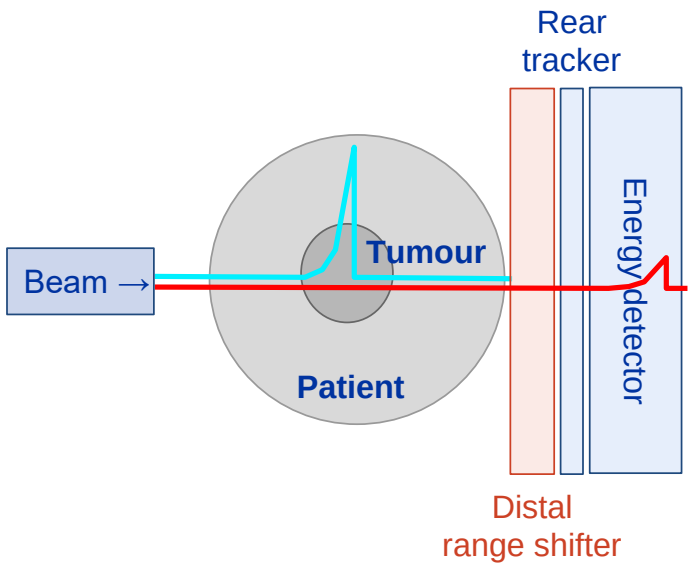
Range shifters

- Distal range shifter can be used to reduce imaging ion range if necessary
- Thicker distal range shifter decreases image quality and makes detector system bulkier
  - thickness up to at least 150mm have been considered

1. At treatment depth, imaging ion flies past detector



2. Add distal range shifter to shift imaging peak to detector



Range shifters

- Proximal range shifter can be used to push imaging ion out of patient into the detector
- Typical proximal range shifter thickness in clinical use up to 45mm

