Mass General Brigham
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A novel degrader system for ultra-fast beam delivery in proton therapy

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Purpose

- Clinical potential of proton therapy not fully exploited due to:
  1. **Slow dose delivery**
  2. **High cost of equipment**
- **Slow energy changes between treatment layers**
  - prolong treatment times
  - limit efficiency and accuracy of treating moving targets
- **Bottlenecks in current technologies**

Cyclotron	• Degrader + Energy Selection System (ESS) • **Switching time: ~100 ms to > 5 s**
Synchrotron	• Slow acceleration time + magnet ramping • **Switching time: ~seconds (MEE: 200 ms)**

- **Expensive and large footprint**
  - rotating gantry → diameter = 10 m, 100 - 200 tons

Goal: To develop a degrader solution capable of
- ☑ **rapid energy modulation**
- ☑ **integration into compact systems**

Methods

To achieve **fast energy switching**, we propose combining

1 Ultra-fast degrader

- **Monte Carlo simulations**
  to optimize degrader-collimator system in terms of material, geometry, and configuration
- **Geometry**
  single-moving, dual-moving, multi-wedge
- **Goal**
  minimize emittance growth, maximize transmission while supporting rapid mechanical motion

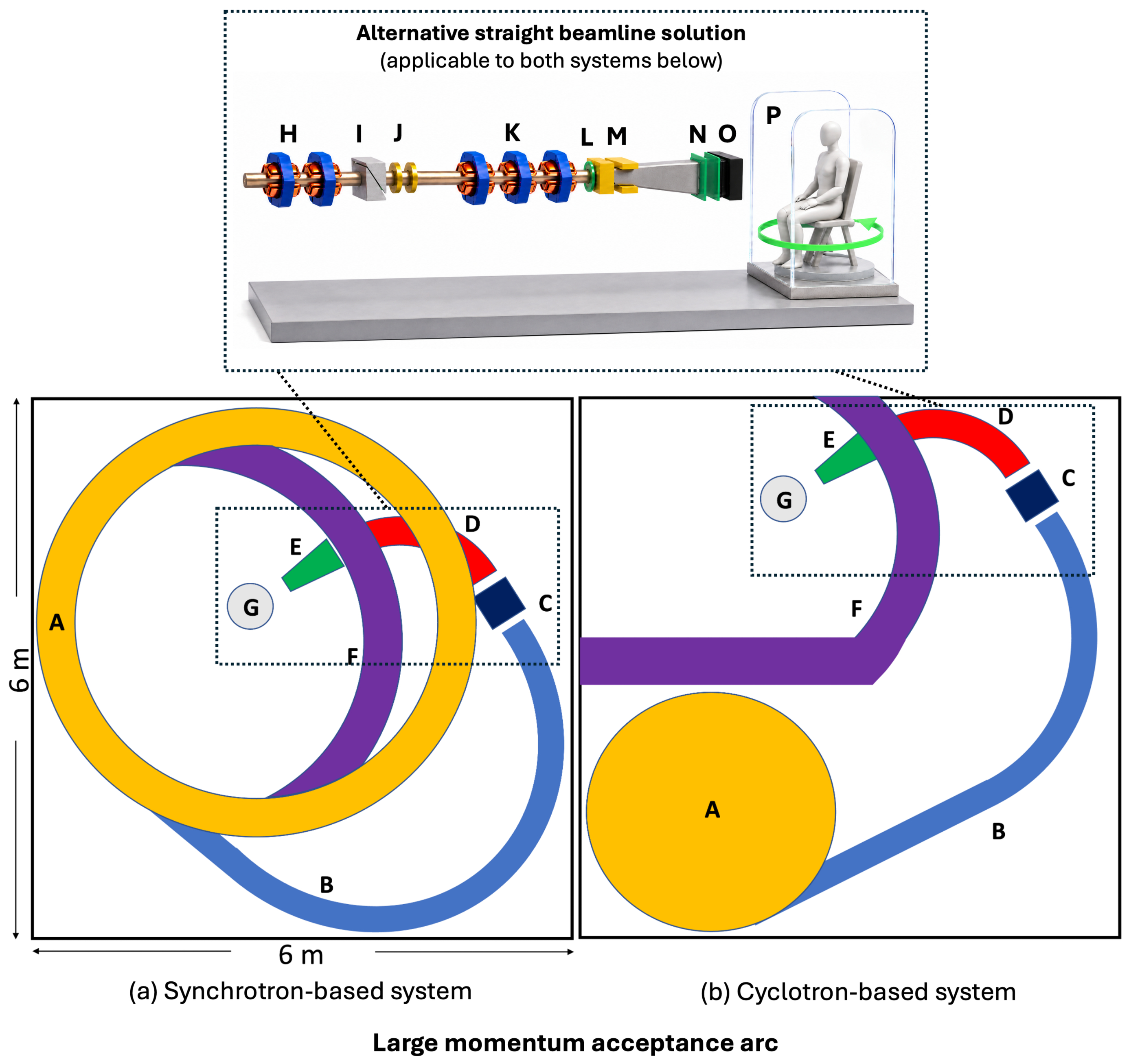
2 Fixed beamline for upright beam delivery

Large momentum acceptance arc
- Based on fixed field alternating gradient (FFA) optics
- Can transport wider momentum range (up to ±30%)
- No need to adjust beamline magnets (time-consuming)
- Curved geometry easier to fit in a compact layout
- Possibility to limit energy spread

OR

Straight beamline with fast quadrupoles
- Simpler but less space-efficient option
- Fast quadrupole ramping speeds compatible w/ switching time

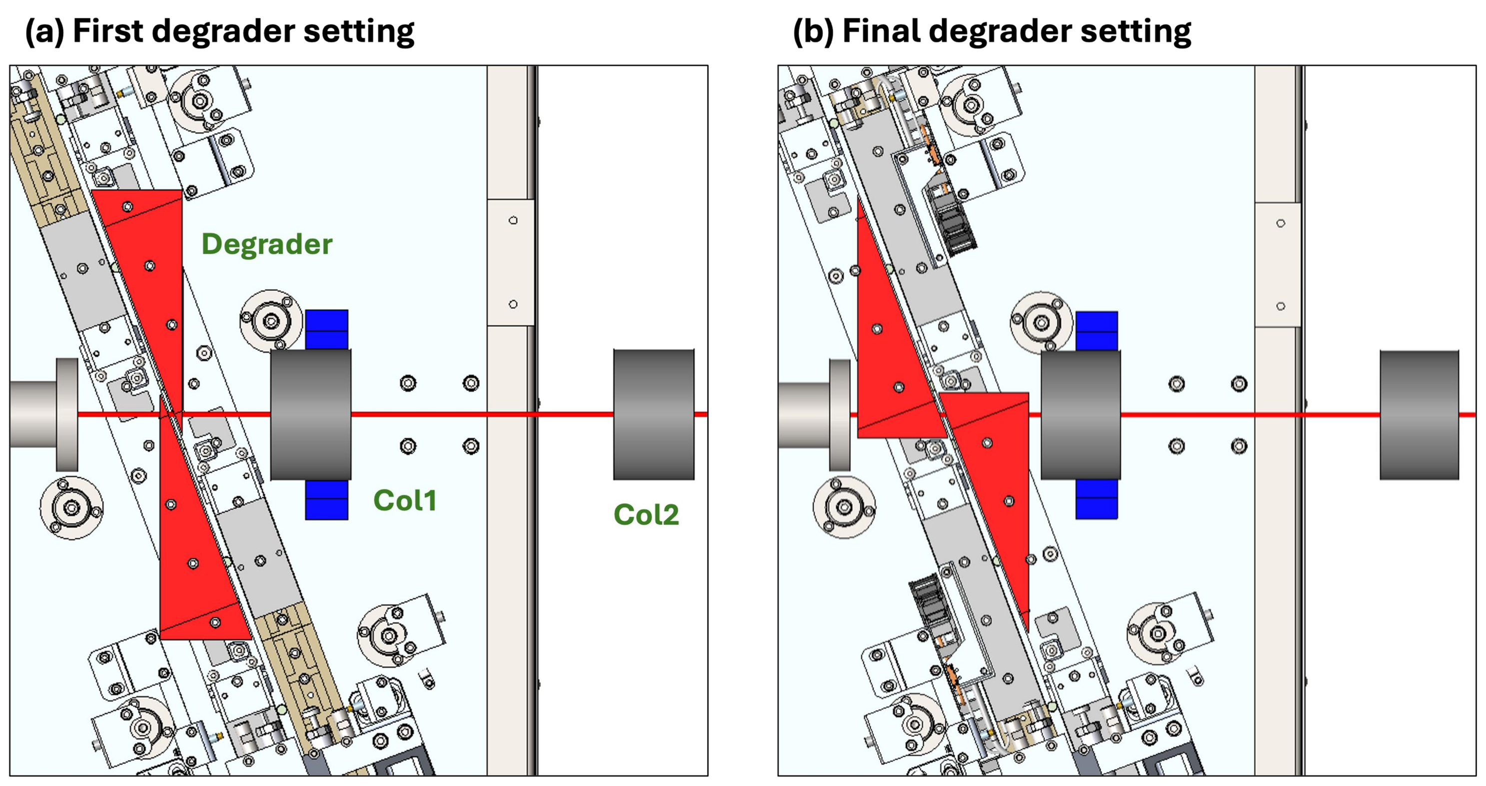
Single fast degrader	• Cyclotron → eliminate ESS and large dipole magnets • Synchrotron → extract highest energy layer and generate remaining layers w/ degrader
Double degrader	• Two sets of degraders • Primary degrader + ESS (deepest layer only) • Fast degrader downstream (remaining layers)



*Treatment room with **A** – synchrotron (left) or cyclotron (right), **B** – beam extraction segment, **C** – ultra-fast degrader system, **D** – FFA lattice or straight beamline (box), **E** – nozzle w/ fast scanning system, **F** – shielding, **G** - patient*

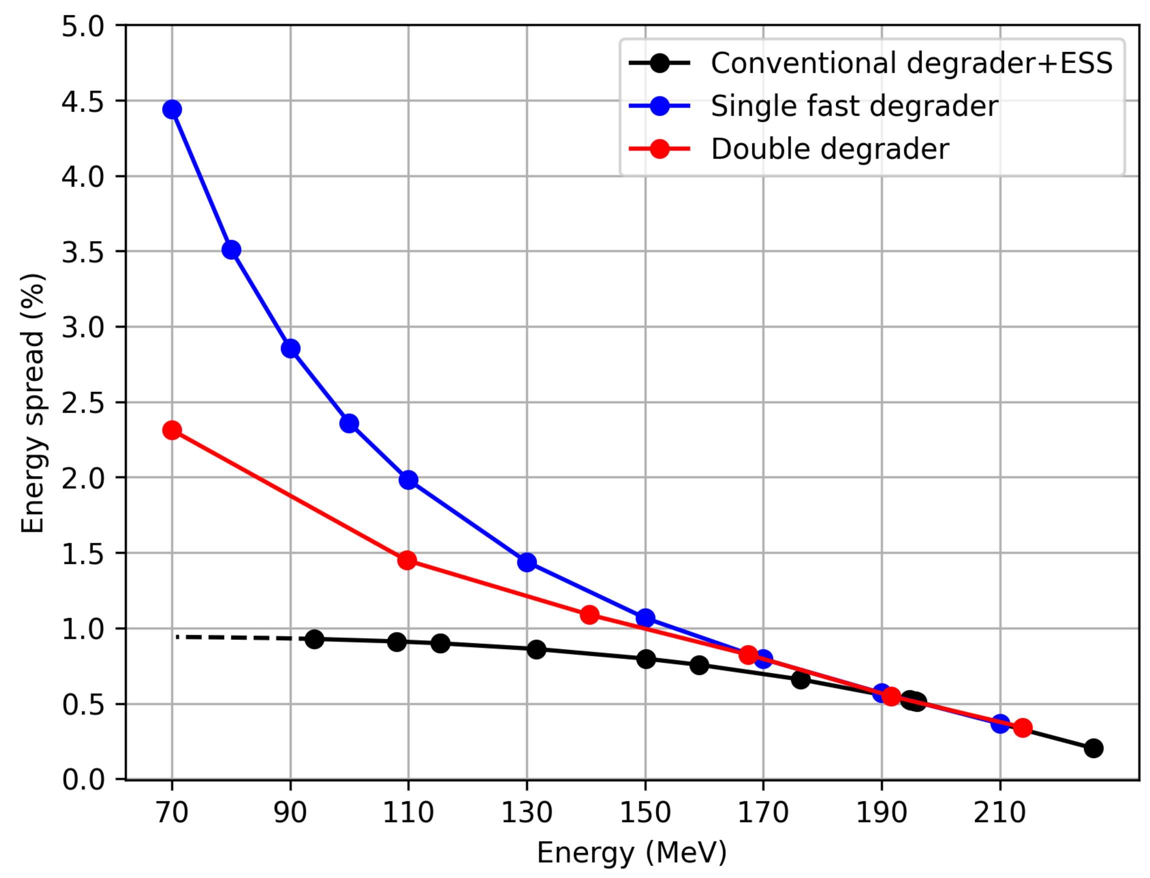
Results

Dual-moving wedge degrader + 2-collimator system



Parameter	Value
Material	Boron carbide
Dimensions	23.4 × 8.8 × 4 cm^3
Moving mass	1 kg per wedge
Maximum displacement	3 mm per 3 MeV step

SWITCHING TIME
10 ms



Double degrader solution for cyclotron-based system
- Lower energy spread than single fast degrader
- Enables fast energy switching without major beamline modifications (upgrades)

Degrader motion dictates energy switching speed
- Cyclotron: no slow beamline components
- Synchrotron: avoids repeated beam acceleration and extraction at each energy change

Conclusions

- Developed a **compact**, **lightweight**, **ultra-fast degrader** enabling energy changes within **10 ms**.
- The degrader is designed to operate with either two beamline configurations: (i) **large momentum acceptance arc**, or (ii) **a straight section with fast ramping quadrupoles**.
- Double degrader **limits energy spread** and **enables upgrades** to existing proton therapy systems.
- This approach accelerates energy modulation by **reducing reliance on slow beamline components** for energy switching.
- This system will considerably:
  - ☑ shorten treatment times, improve patient comfort, promote higher throughput
  - ☑ increase efficiency in implementing motion-mitigation strategies
  - ☑ enables new delivery techniques such as proton arc therapy and FLASH

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