CONCEPTUAL DESIGN OF TR100+: AN INNOVATIVE SUPERCONDUCTING CYCLOTRON FOR COMMERCIAL ISOTOPES PRODUCTION

Yuri Bylinski

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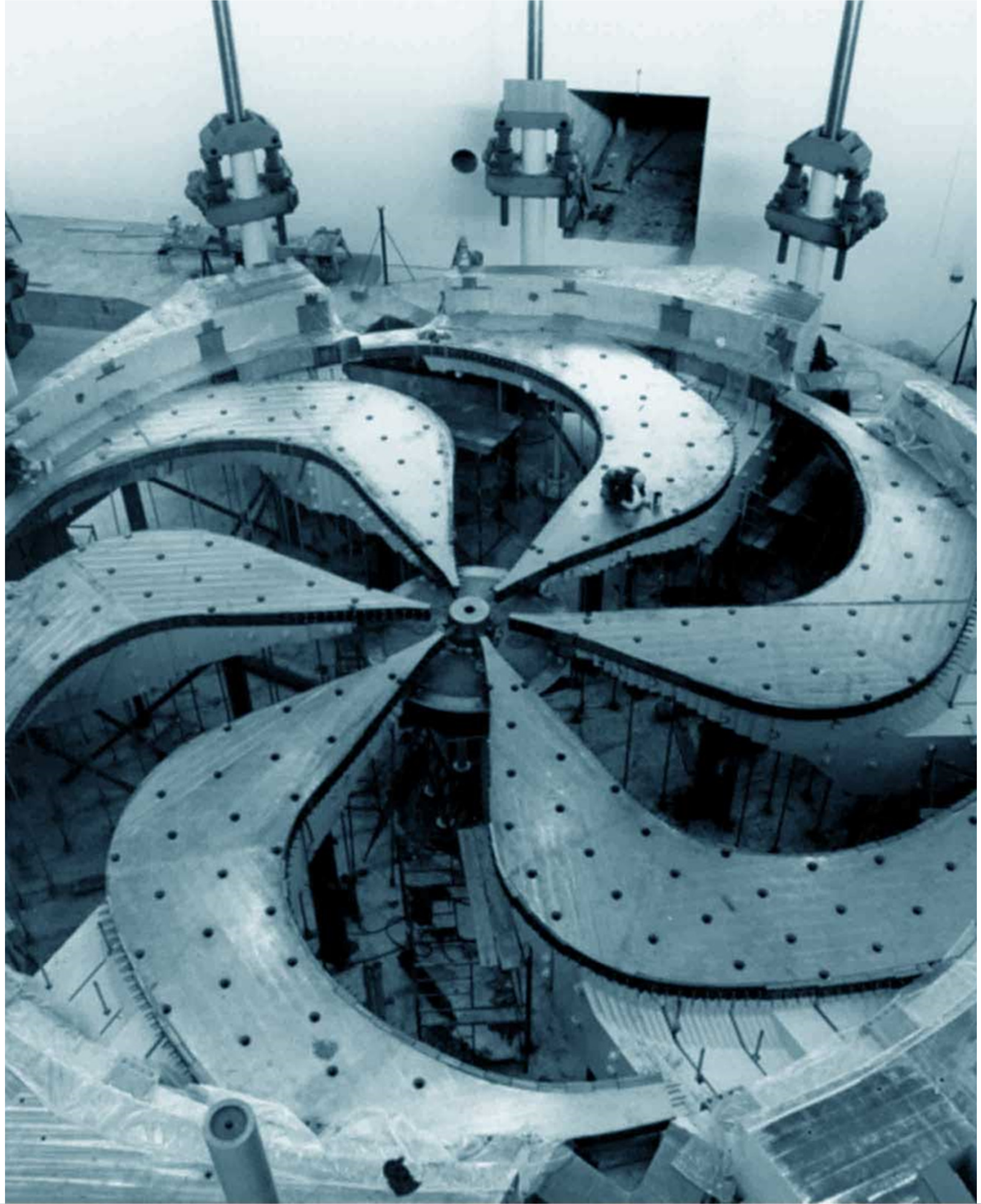


Discovery, accelerated

Outline

- Motivation
- Major machine parameters
- Conceptual design initial output
- Challenges
- Look forward

Existing medical cyclotrons

There are typically two main types of commercial medical cyclotrons:

- for medical isotope production
  - H− machines
  - high current (0.05-1 mA)
  - low-to-medium energy (7−70 MeV)
- for proton therapy
  - proton machines
  - low-current (<1μA)
  - high-energy (200−400 MeV)

Pet Cyclotrons

Well established:

- IBA: Cyclone 18/9 => KIUBE
- GE: PETtrace
- Siemens: Eclipse
- Sumitomo: CYPRIS
- ACSI (EBCO): TR19 => TR24

Newcomers:

- ABT Molecular Imaging: BG-75
- CIAE: CYCIAE-14
- Best Cyclotrons
- Compact SC cyclotrons (table-top “coffee makers”)
  - AMIT
  - LOTUS
  - ION-12SC

PT Cyclotrons

Established:

- Varian (Germany): ProBeam-250 MeV
- IBA (Belgium): S2C2
- Sumitomo (Japan): P235
- Mevion (USA): S250

Newcomers:

- CIAE (China): CYCIAE-230
- ASIPP, Hefei (China) + Dubna (Russia): SC200 (SC230)

TRIUMF

Medical interest in ~100+ MeV protons

- Ac-225 and Bi-213 – main drivers of radiopharmaceutical developments for treatment of cancers (Melanoma, Prostate and Pancreatic)
- Sr-82 – PET agent in myocardial perfusion imaging
- At-211, Ti-45 and Ra-223 – proven commercial demand
- Ra-224, Pb-212 and Bi-212 – research interest

Cyclotrons in 100 MeV niche

70−100 MeV range has just taken off the ground:

- IBA 70 MeV family
- Best Cyclotrons 70P
- CYCIAE-100 (Beijing,China)

All are H^- machines

Beam losses due to the electromagnetic stripping is a dominant intensity limiting factor

Low magnetic field and large magnet size is a compromise to control beam losses at high intensity

Direction to alternative solution

To be efficient and economically attractive:

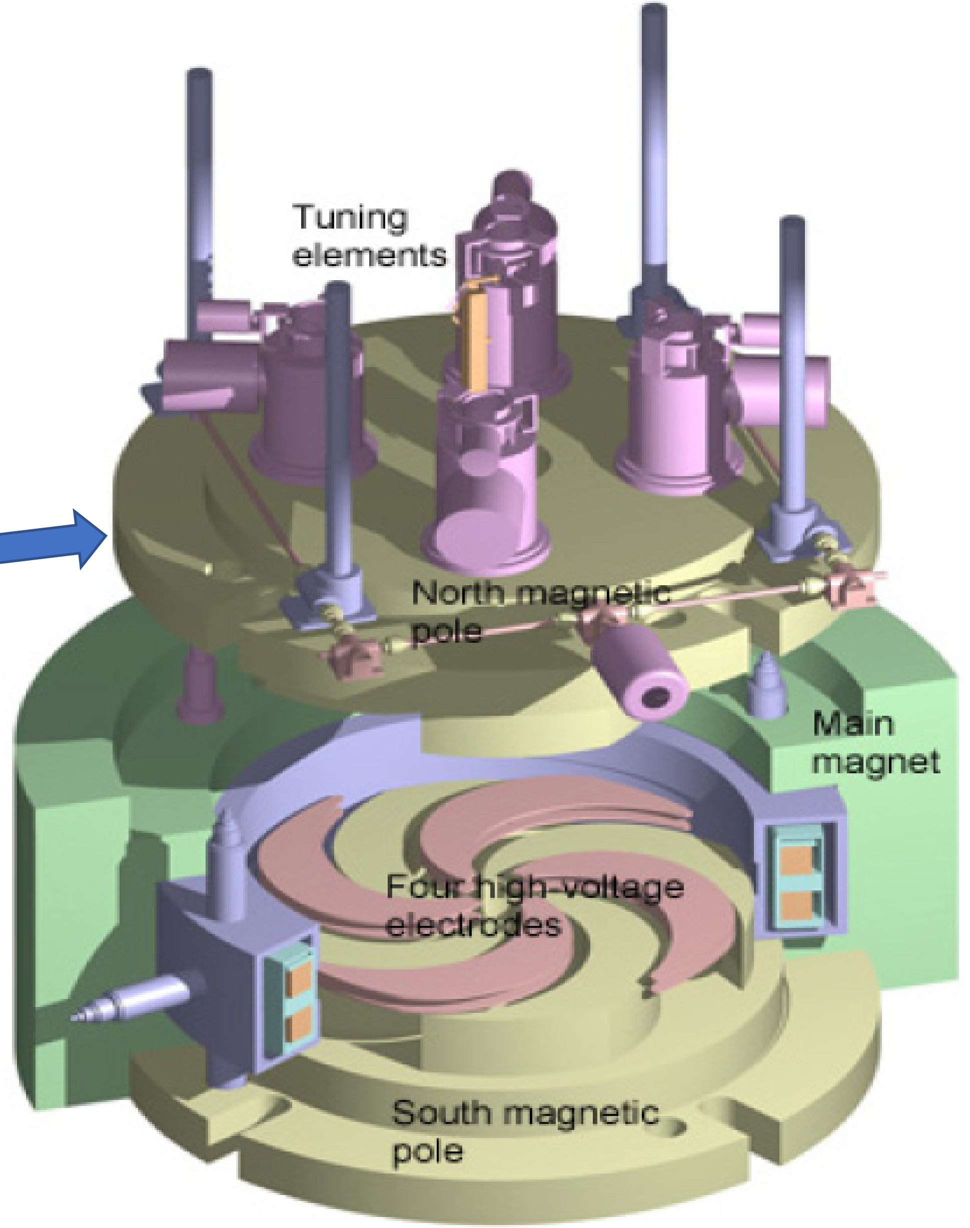
- Keep machine size small => high magnetic field
- Reduce operating costs => superconducting magnet

Possible way to go:

- Drop out H^- option => switch to H_2^+
  - solves electromagnetic stripping issue (higher binding energy)
  - preserves stripping extraction benefits
  - no need for turns separation
  - preserves high machine acceptance
- Side benefit of S/C magnet: high magnetic field reproducibility and linearity because of yoke saturation

Preceding H_2^+ Cyclotron Design Studies

- SCENT project (Catania, Italy)
- IsoDAR/DAEδALUS project (MIT, USA)



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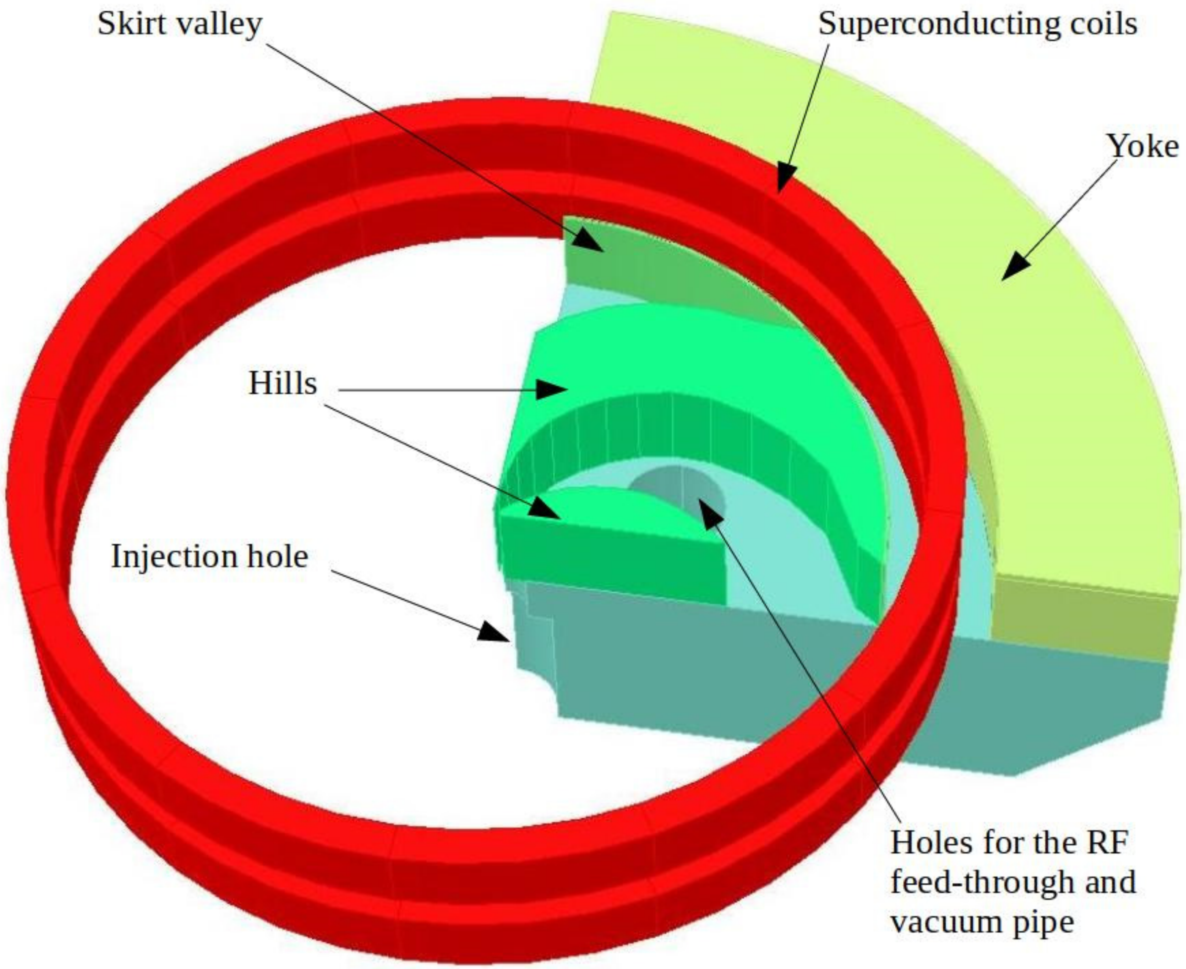
TR100+ Main Parameters (conceptual design preliminary study)

Parameters	Value
Particle accelerated	H_2^+
Injection energy (keV/n)	25
Extraction energy (MeV/n)	100−150
Beam intensity (μA)	800
Number of sectors	4
Magnet diameter (m)	3.8
Magnet height (m)	2.0
Injection scheme	Axial + external ion source
Extraction	p by stripping extraction
Coils	2 superconducting coils
Number of RF cavities	2
RF harmonic number	4
RF frequency (MHz)	~97
Maximum dee voltage (kV)	120

OPERA Magnetic Field Model

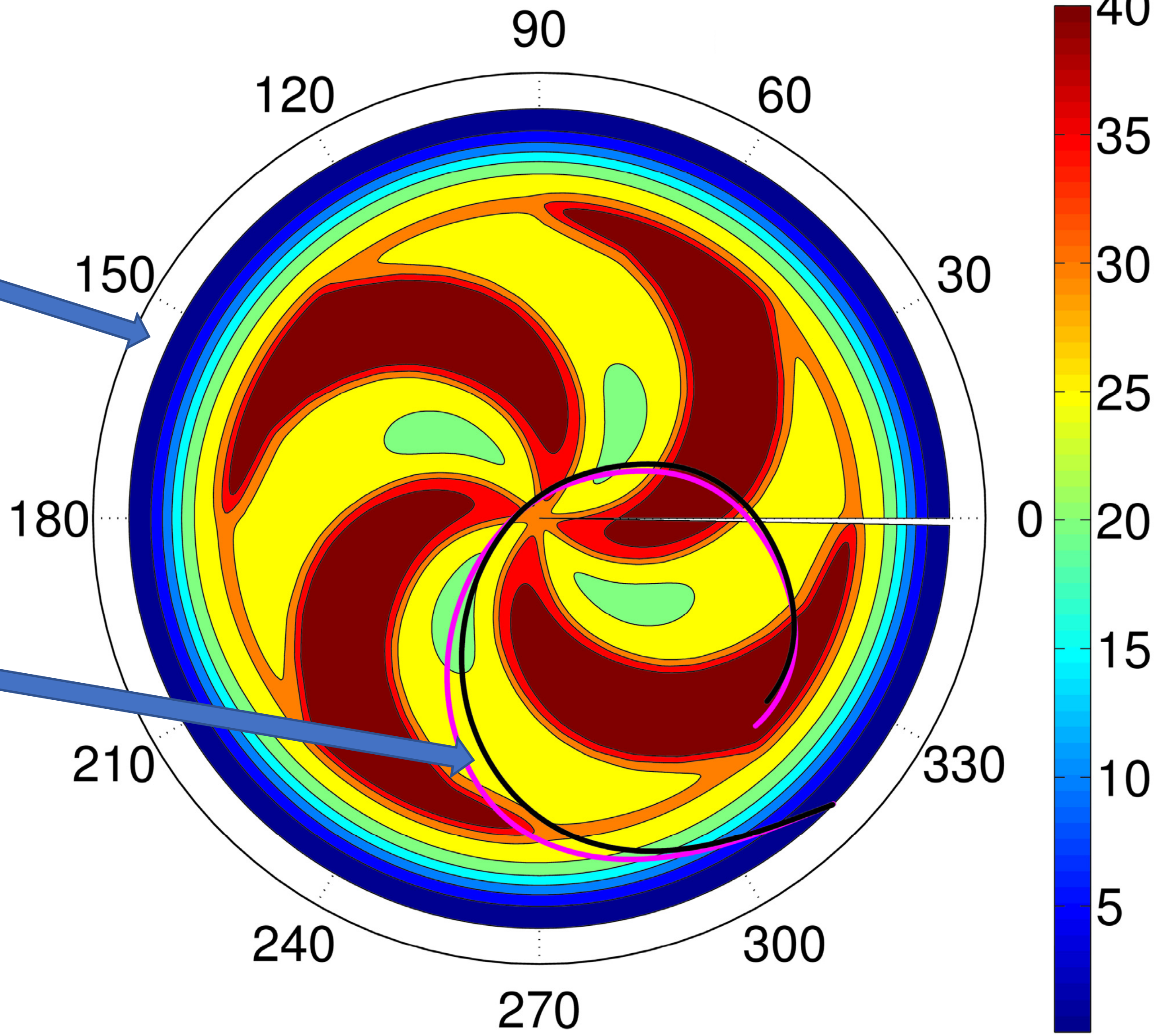
Parameters	Value
Hill gap (cm)	4.5
Pole radius (cm)	106.5
Sector azimuthal width (deg)	40 - 46
Pole spiral angle (deg)	20 - 70
Mean magnetic field (T)	3.1 - 3.7
Max. magnetic field (T)	4.5
Max. current density (A/mm2)	46



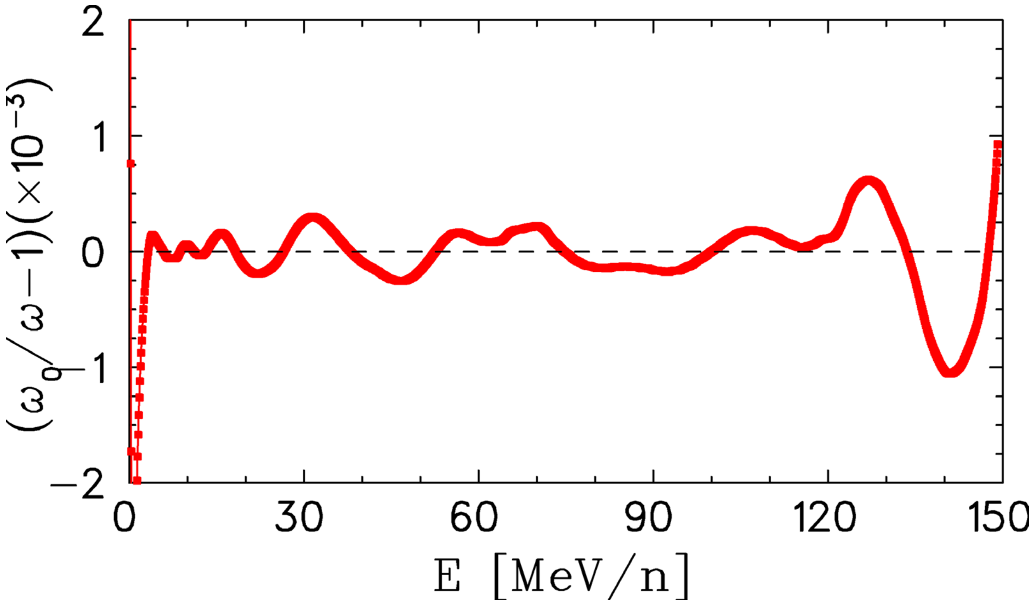
Magnetic Flux Density, Extraction Trajectories

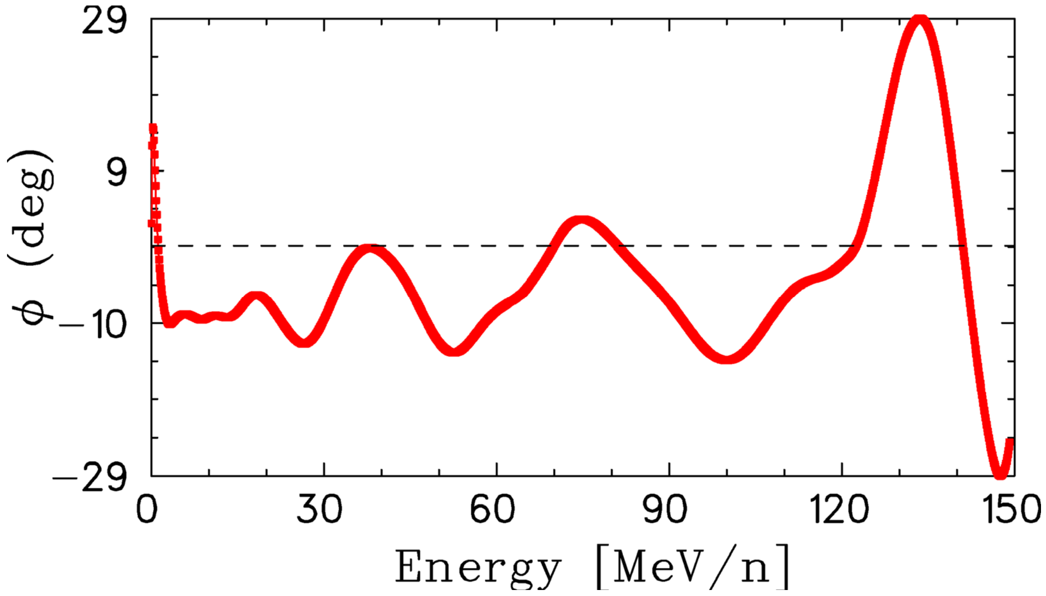
Bz(r, θ) contour in the median plane (kG)

Extraction trajectories of 150MeV (magenta) and 140MeV (black) protons after stripping (example)

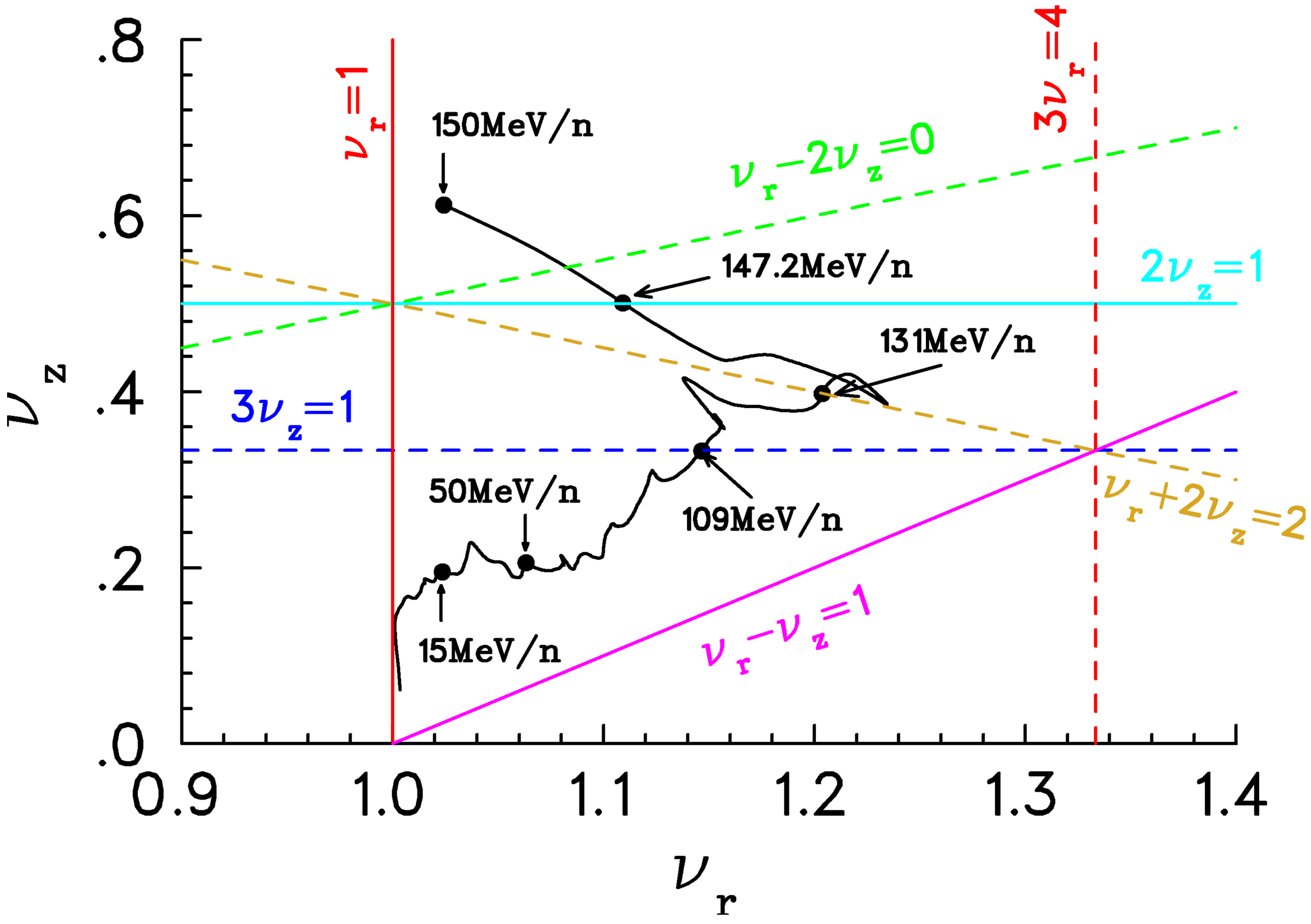


Isochronism & Phase





Tune diagram



Coupling resonance $\nu_r - \nu_z = 1$ is avoided

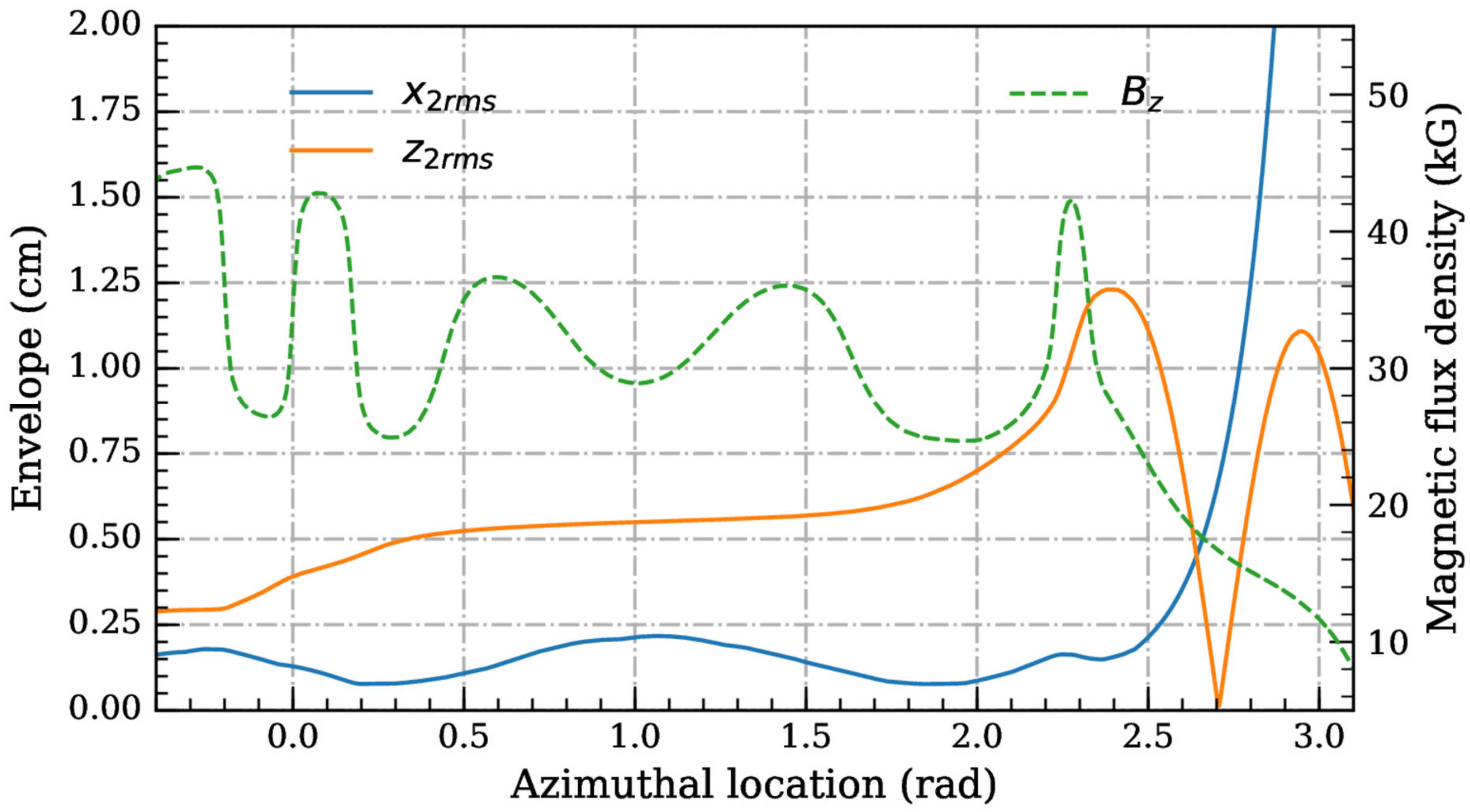
Half-integer resonance $2\nu_z = 1$ occurs at ~147.2 MeV/n

Beam size at extraction

Simulation of beam envelope along extraction trajectory
Circulating emittance:
0.54 π mm.mrad (4rms, normalized)

Axial beam size (orange, solid)
Radial beam size (blue, solid)
Magnetic field strength (green, dash)

Magnetic channel is needed to pass fringe field



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Intensity Limitation

In both: H_2^+ and H− compact cyclotrons the space charge effects are strongest at the first turns

The intensity limit is driven by:

- vertical space charge tune shift
- longitudinal space charge effect

TR30 demonstrated upper limit of ~1.0 mA (with 5mA injected dc beam)

For TR100+, current intensity limit scales to ~800 uA of extracted protons

Beam Losses Constraints

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Two predominant types of beam loss in TR100+:

- electromagnetic dissociation (Lorentz stripping)
- interactions with residual gas

H_2^+ has binding energy of last electron of 2.75 eV, ~ 3.6 times larger than in H^- case

Unfortunately, the lowest electronic state of H_2^+ has 19 bound vibrational states

Ions in a vibrational state above 16 will dissociate during acceleration in the proposed configuration: ~2% of the beam could be lost

Vacuum has to be better than 1.0 × 10−7 Torr to maintain beam loss due to residual gas stripping below 1.0%

Other Challenges

Low charge-to-mass ratio (1/2) of H_2^+ machine has its drawbacks compared to H^- option:

- twice higher injection energy (50 keV)
- twice as high spiral inflector electric field
- twice as large energy gain on first turns => RF voltage also has to be twice as high (120 kV)

Look Forward

Only preliminary conceptual consideration has taken place so far.

Next steps in the design effort:

- Injection line and center region design
- Sectors spiral shape optimizations for better vertical focusing
- Design of rf cavities to operate at high voltage and high power
- Exploration of vibrational states suppression in the ion source
- High temperature superconducting coils option engineering

Full scale project necessities:

- Converge on requirements/specifications
- Develop realistic schedule (4-5 years)
- Secure funding
- Define and engage partners
- Build up dedicated project team

Thank you!