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ITRF WP3 Radiobiology Synchrotron Study

Mark Johnson | ITRF Six-Month Review

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Introduction

ITRF WP3 Context

- **ITRF WP3** aims to **compare** options based on **conventional technologies** against the baseline **LhARA** facility design

- This includes the evaluation of a **synchrotron**, with a **injector** based on **established ion sources** and pre-acceleration methods

- Currently parameterising a small synchrotron design, adapted from work published by the **CERN NIMMS** project

> At present, we are **not considering** the synchrotron as a **drop-in replacement** for the LhARA **FFA**

Design Basis

Compact, Room Temperature Synchrotron

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Key Requirements:

- Synchrotron is primarily designed for the **most likely radiotherapy ions** (H^+, $^4He^{2+}$ and $^{12}C^{6+}$), without excluding heavier ions in future

- Aim for stored intensities compatible with **FLASH regimes**, of order **10^{10} ions** per spill

- Machine fits within the **circumference** of the **LhARA FFA** (21.86 m) with **similar beam energies**

- Use accessible, conventional technologies e.g. **room temperature** magnets

Examples

CERN NIMMS and ELENA

[1] H.X.Q. Norman *et al.*, Proc. IPAC '22, **THPOMS028** (2022)
[2] M. Vretenar *et al.*, J. Phys.: Conf. Ser. **2420** 012103 (2023)
[3] V. Chohan et al., Extra Low Energy Antiproton Ring (ELENA) and its Transfer Lines – Design Report, **CERN-2014-002** (2014)

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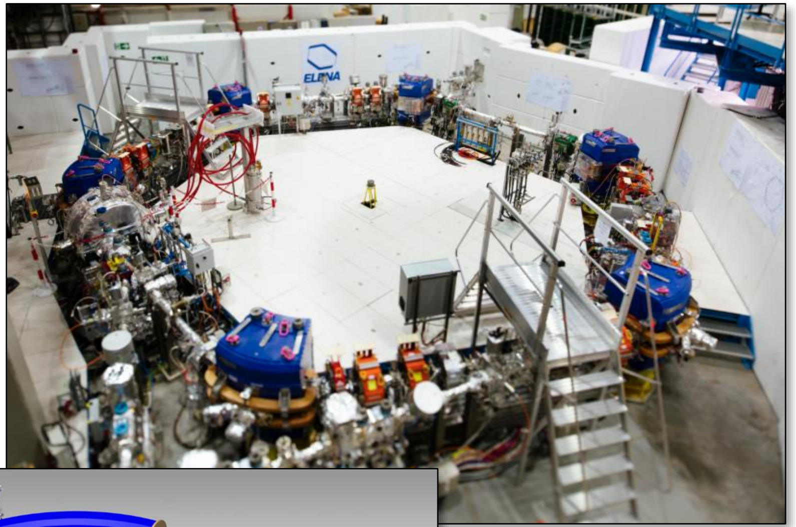
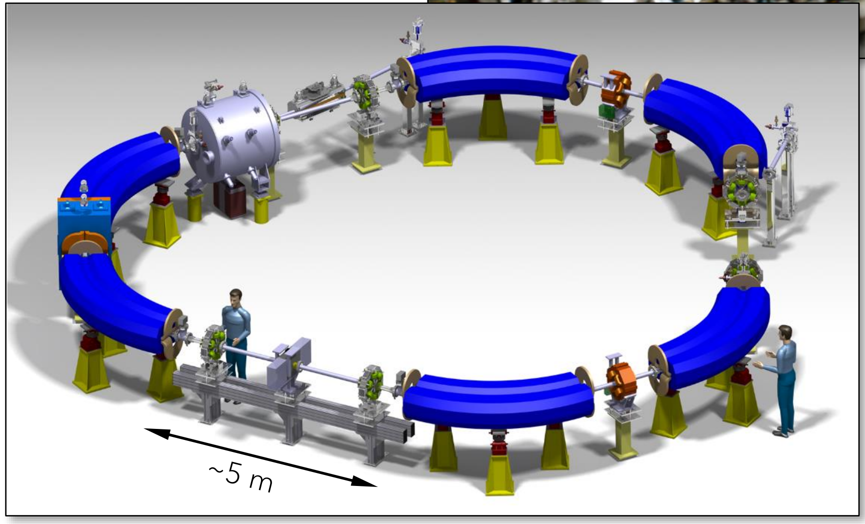
- NIMMS have proposed **compact synchrotron** designs for $^{12}C^{6+}$ and $^{4}He^{2+}$ ions [1,2]
- Designs target **FLASH** dose rates, at **relatively high energies** (430 MeV/u for $^{12}C^{6+}$) relevant to clinical treatment
- NIMMS designs build on CERN experience with small hadron synchrotrons like **ELENA** [3]
- **Slow-cycling** synchrotron designs (~1 Hz)





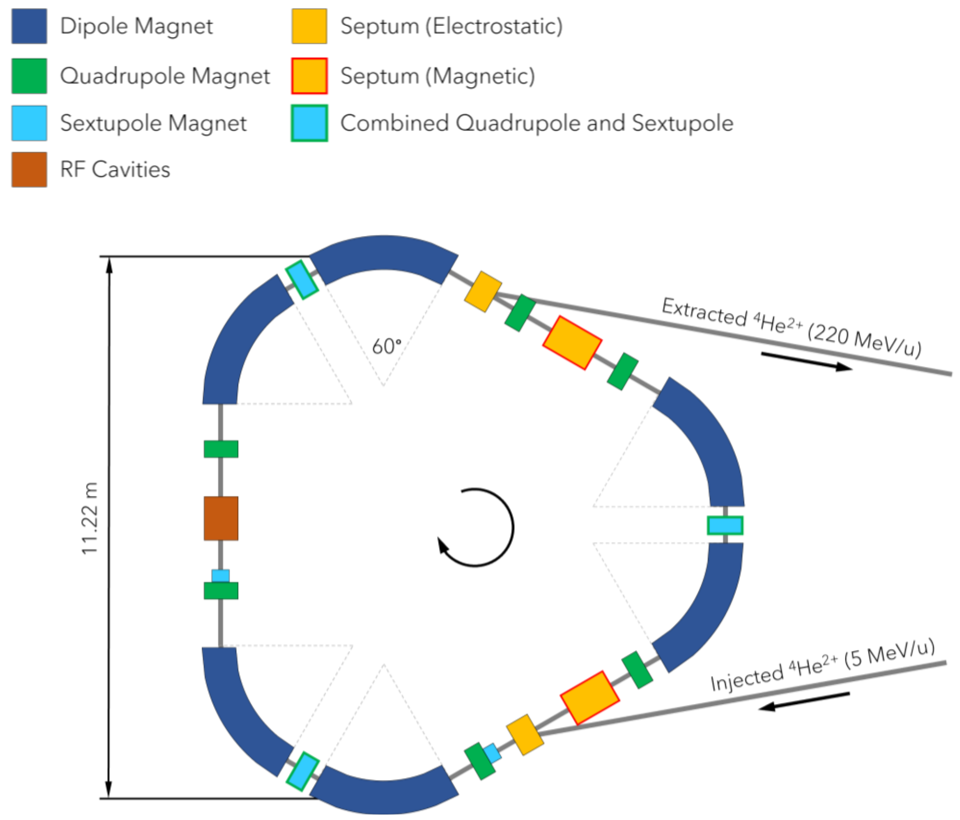
Above: ELENA decelerator at the CERN AD
Below: Render of the NIMMS $^{4}He^{2+}$ synchrotron design

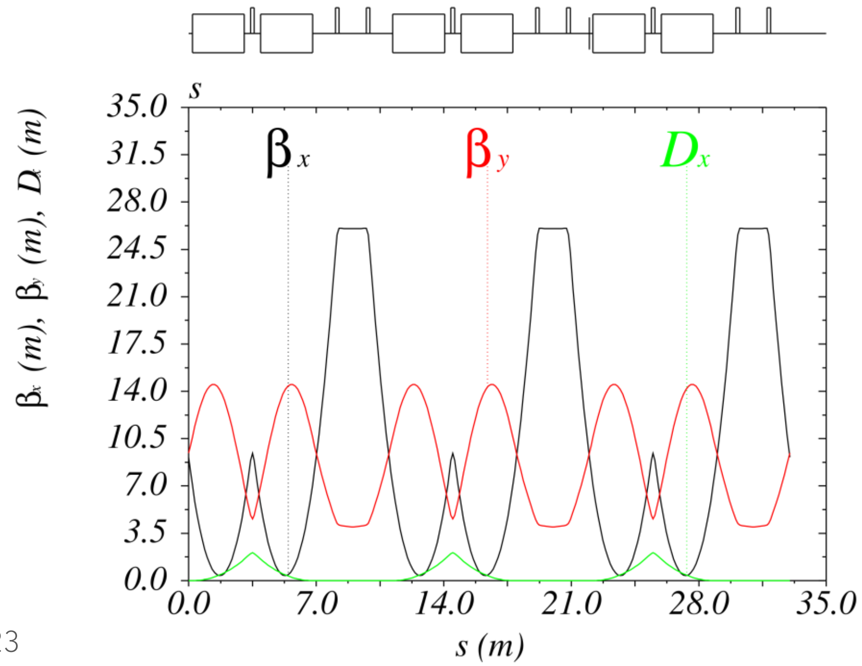
NIMMS $^4He^{2+}$ Design

Helium Ion Synchrotron

[1] M. Vretenar *et al.*, J. Phys.: Conf. Ser. **2420** 012103 (2023)
[2] X. Zhang, arXiv:2007.11787 [physics.acc-ph] (2020)

- Small (~33 m circumference) synchrotron [1] comprised of **three achromat lattice cells** [2]
- Room-temperature **60° sector dipoles** operating up to 1.65 T, enable $^4He^{2+}$ acceleration to **250 MeV/u**
- **Dispersion-free straights** accommodate **injection**, **extraction** and RF hardware





ITRF Synchrotron Design

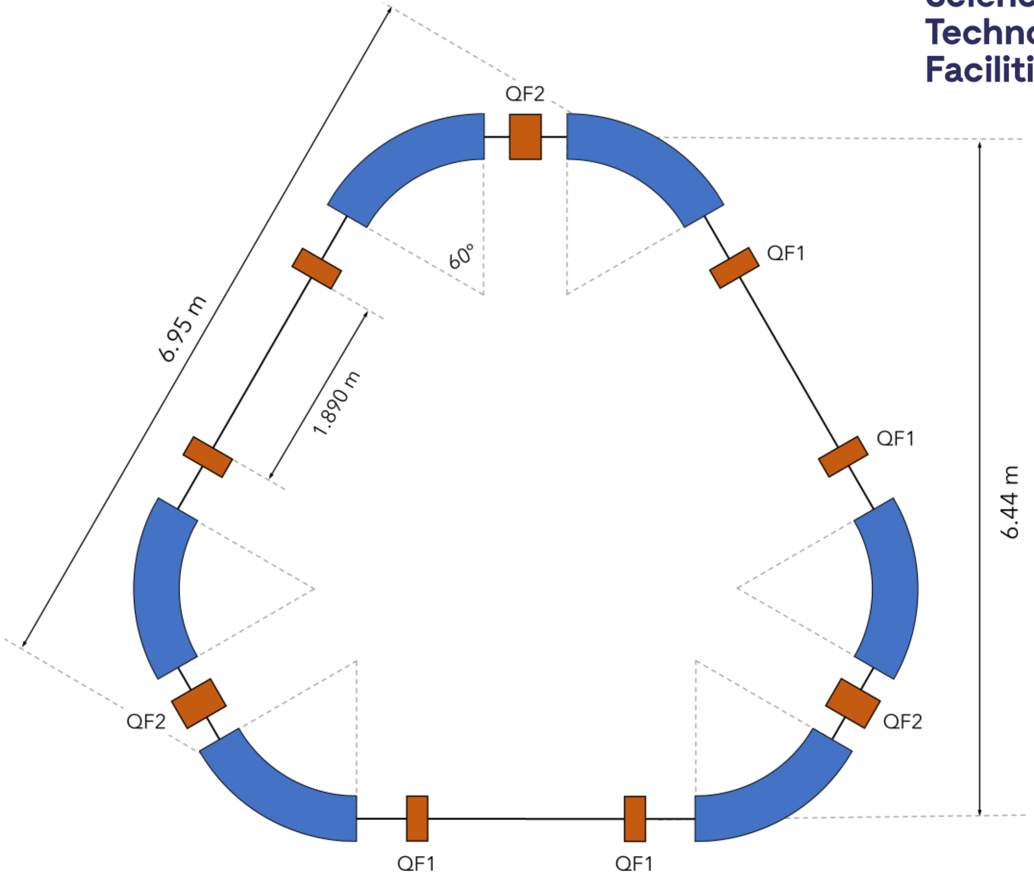
Scaled NIMMS Layout

[1] M. Vretenar *et al.*, J. Phys.: Conf. Ser. **2420** 012103 (2023)

Synchrotron (~21.3 m circumference) based on a **scaled** version of the **NIMMS synchrotron** design [1]

- 1.30 T **sector dipole** magnets with a small defocusing gradient
- **QF1** quadrupoles used for **working point** adjustment
- **QF2** quadrupoles used for **dispersion cancellation**

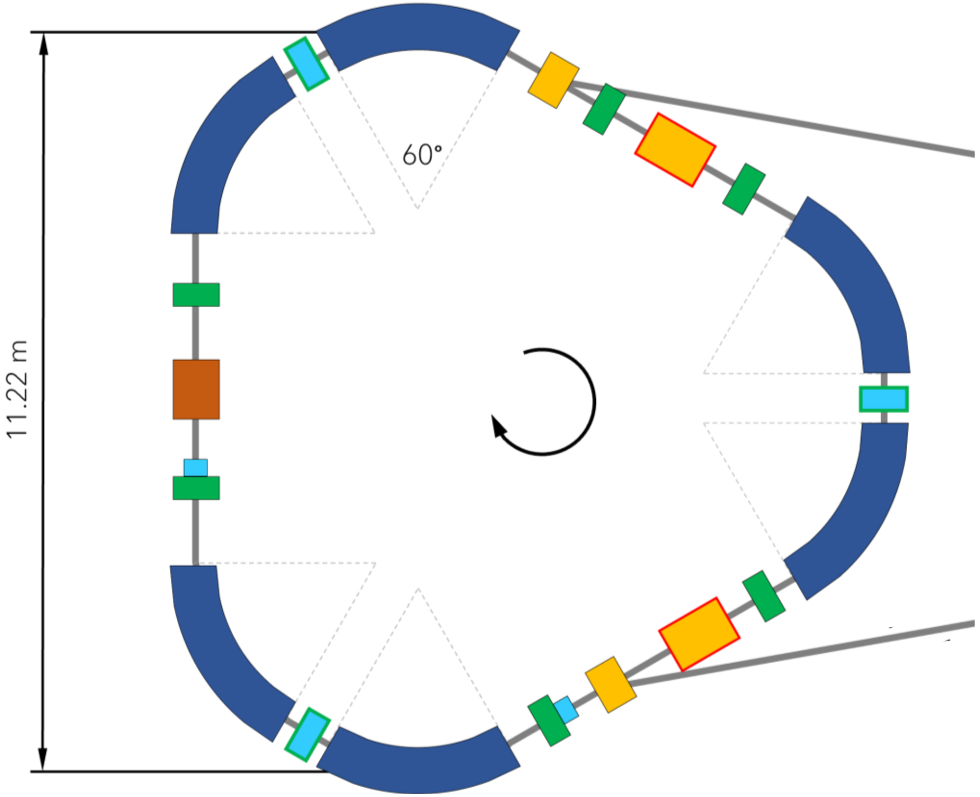
Parameter	Value	
Dipole radius [m]	1.45	
Dipole field [T]	1.30	
Max. Rigidity [T m]	1.89	
Ion Species	H^+	$^4He^{2+}$, $^{12}C^{6+}$
Max. Energy [MeV/u]	80*	33.4
Orbital Frequency [MHz]	5.48	3.67

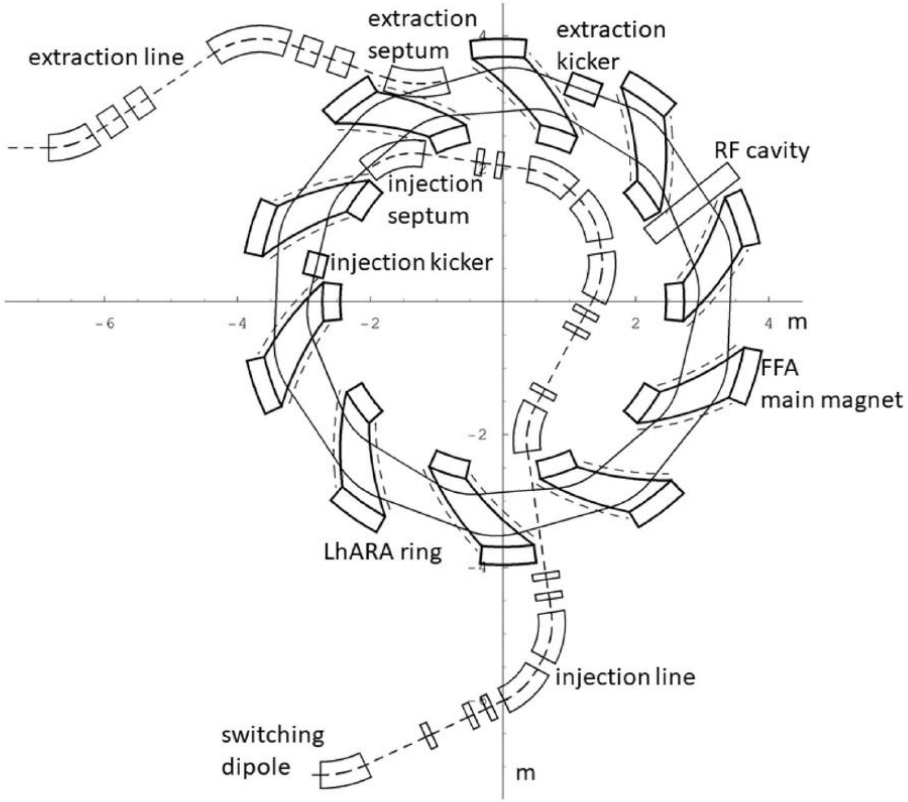


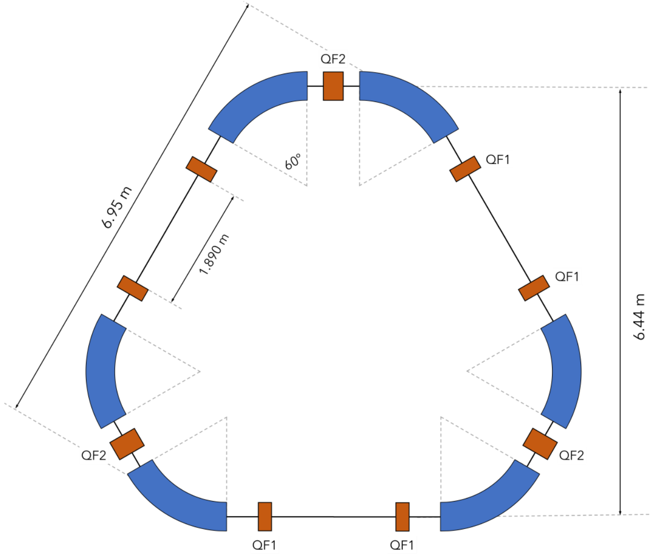
*Limited by assumed RF cavity bandwidth (1.5 – 5.5 MHz)
Dipoles can accommodate protons up to 155 MeV

Machine Footprints

Approximately to Scale







Left: NIMMS $^4He^{2+}$ synchrotron (33.0 m)
Above: LhARA FFA (21.9 m)
Right: ITRF WP3 synchrotron (21.3 m)

ITRF Synchrotron Design

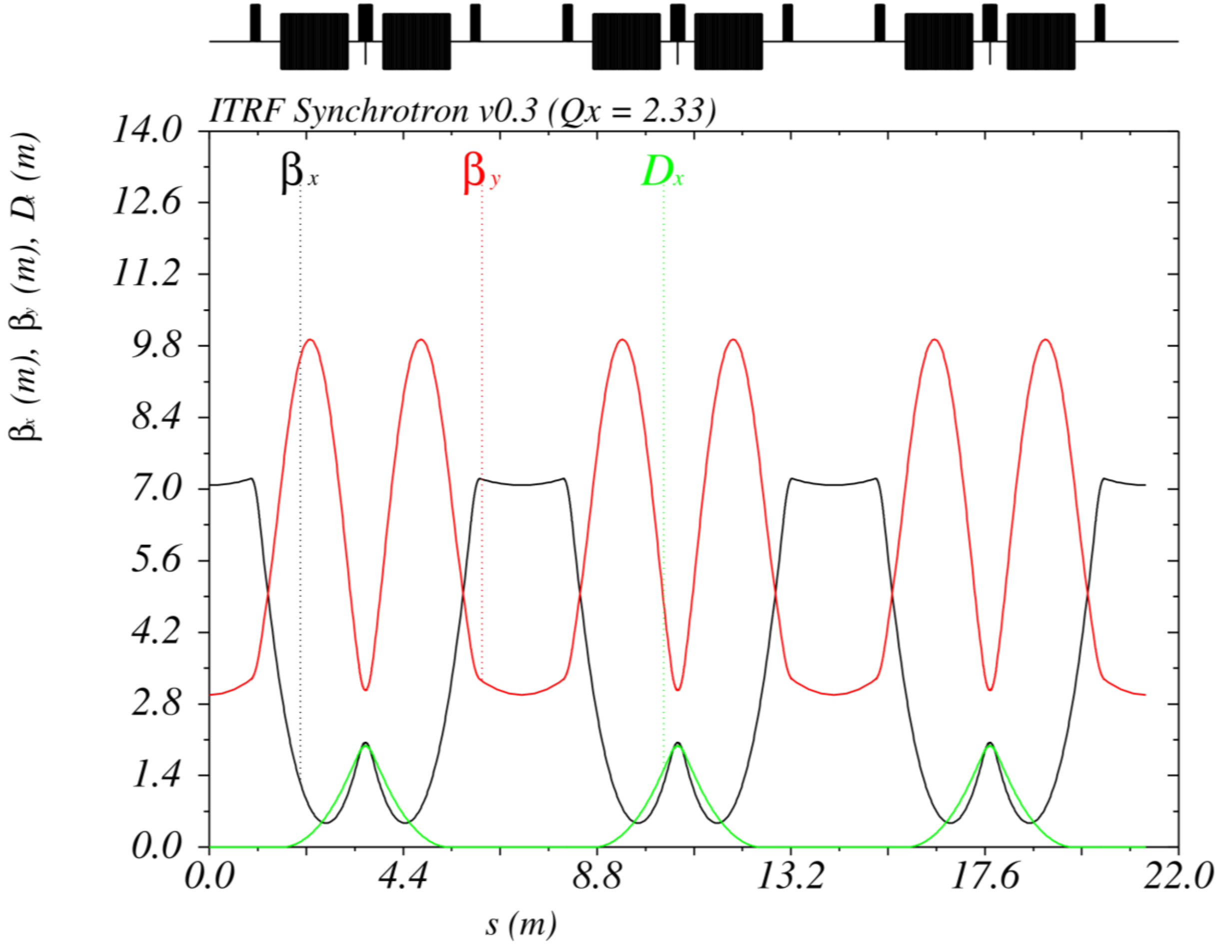
Optics and Key Parameters

[1] R. Taylor *et al.*, J. Phys.: Conf. Ser **2420** 012101 (2023)

Optimised the lattice using a semi-analytic model to **maximise** the accessible **range of working points**

Optics are tuned near a **third-order** betatron **resonance** to enable **RF knockout** beam extraction [1]

Parameter	Value
QF1 strength [m^{-2}]	3.23
Maximum β_x, β_y [m]	7.20, 9.92
Maximum D_x [m]	1.98
Betatron Tunes Q_x, Q_y	2.33, 0.71
Natural Chromaticities ξ_x, ξ_y	-4.36, -5.10



ITRF Synchrotron Design

Optics and Key Parameters

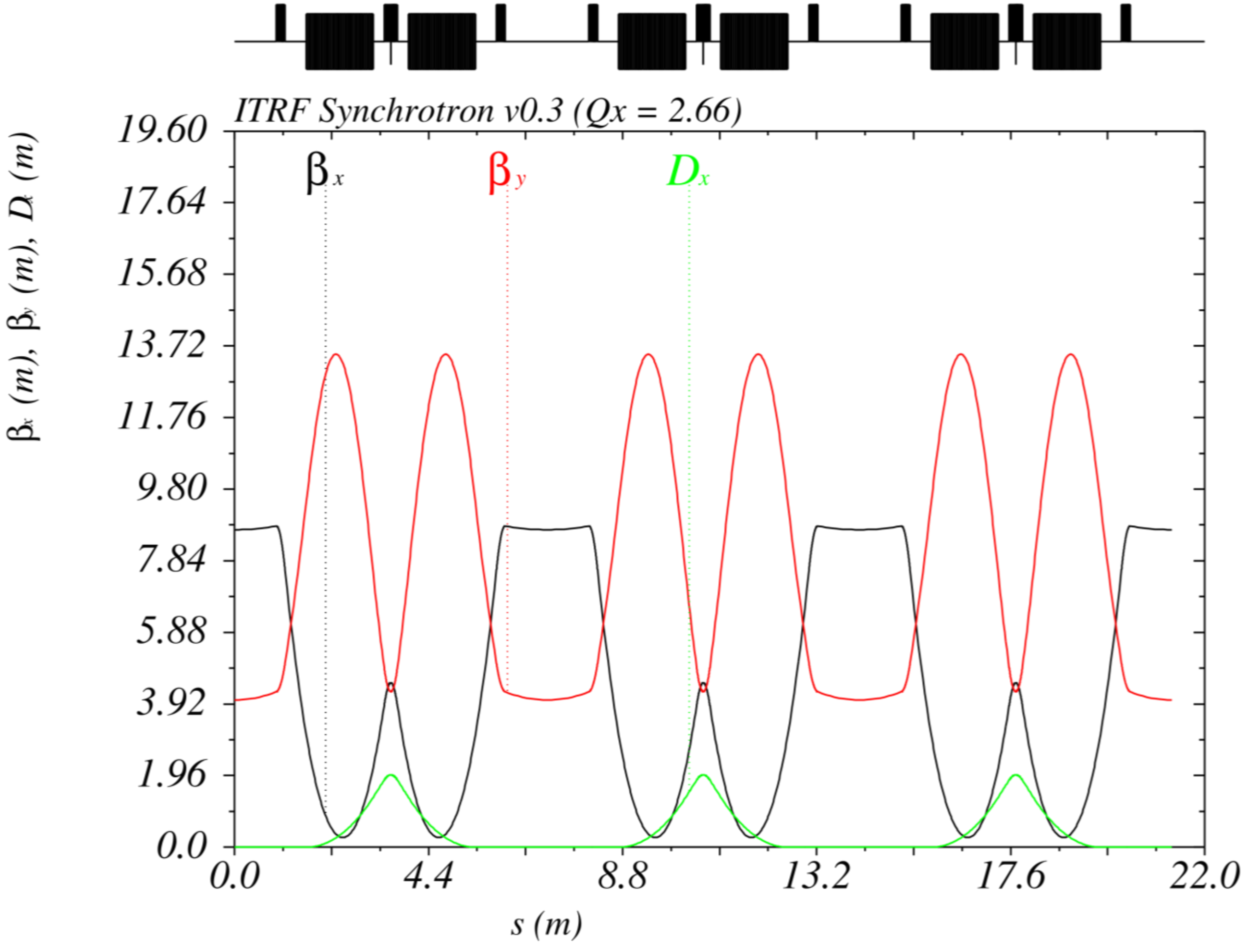
[1] R. Taylor *et al.*, J. Phys.: Conf. Ser **2420** 012101 (2023)

Optimised the lattice using a semi-analytic model to **maximise** the accessible **range of working points**

Optics are tuned near a **third-order** betatron **resonance** to enable **RF knockout** beam extraction [1]

Synchrotron tuning range includes **two viable working points**

Parameter	Value
QF1 strength [m^{-2}]	3.72
Maximum β_x, β_y [m]	8.95, 13.63
Maximum D_x [m]	1.98
Betatron Tunes Q_x, Q_y	2.67, 0.52
Natural Chromaticities ξ_x, ξ_y	-6.66, -6.80



Beam Injection

Injector Chain

[1] M. Vretenar *et al.*, J. Phys.: Conf. Ser. **2420** 012103 (2023)
[2] U. Amaldi et al., *A Facility for Tumour Therapy and Biomedical Research in South-Eastern Europe*, Vol. 2 (2019)
[3] E. Benedetto, CERN-NIMMS-Note-008 (2022)

NIMMS propose [1] a **conventional injector** chain based on **CERN Linac 4**

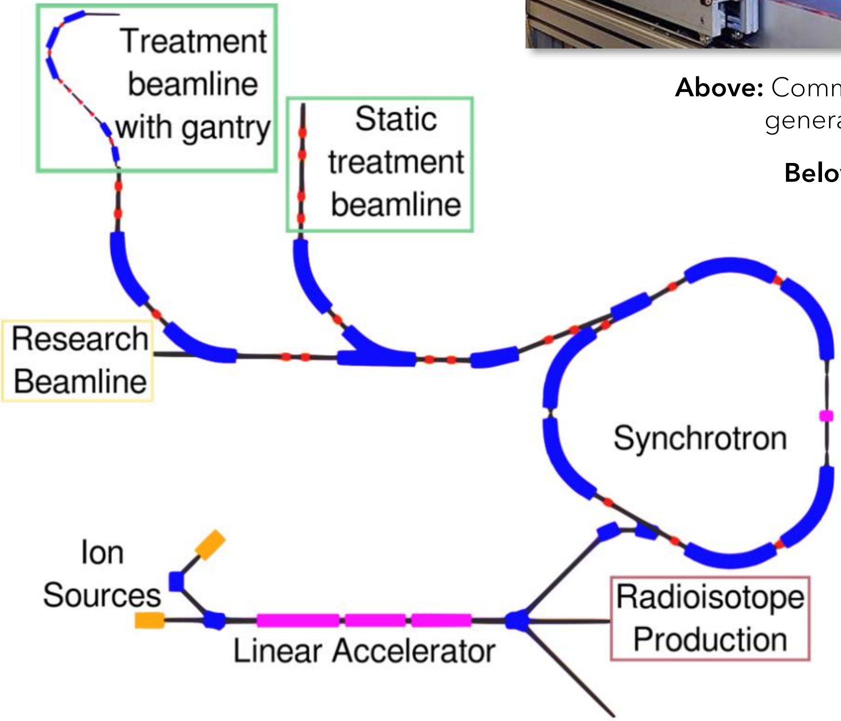
- Multiple **ECR sources** are envisioned, based on the SEEIST [2] injector and commercial *Supernanogan* source
- **RFQ** followed by one (two) **DTL tanks** to inject ions (protons) at 5 MeV/u (10 MeV)

Injection energies are primarily influenced by [3]

- **Multi turn injection** dynamics
- **Space charge** tune shift
- Stripping foil efficiency

Above: Commercial *Supernanogan* ECR source generating up to 2 mA H^+ or 200 μA C^{4+}

Below: Schematic layout of NIMMS He synchrotron and injector



[1] U. Amaldi et al., *A Facility for Tumour Therapy and Biomedical Research in South-Eastern Europe*, Vol. 2 (2019)

Beam Injection

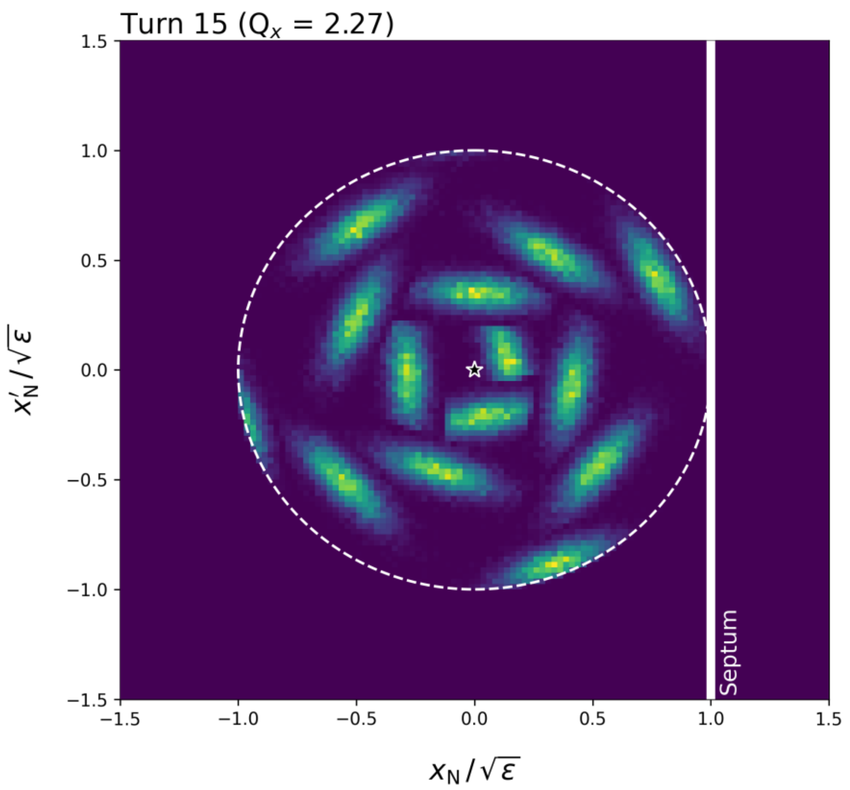
Multi Turn Injection

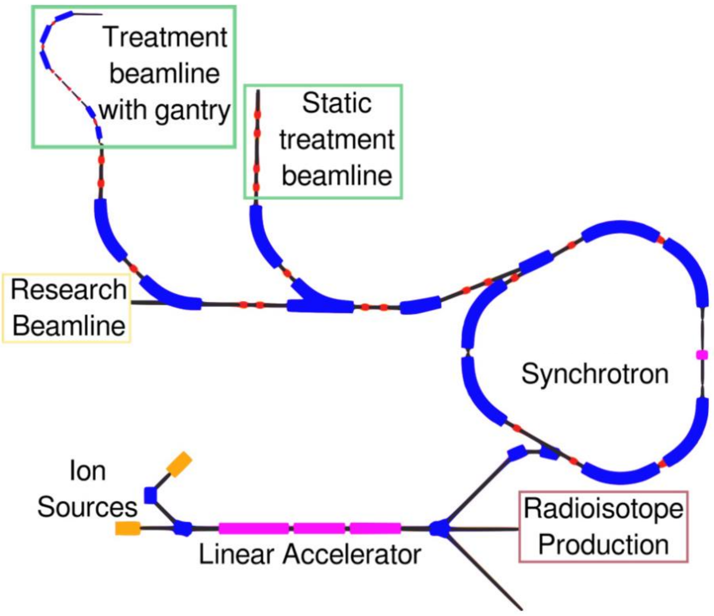
Ions are accumulated over several turns via **MT injection** or "phase space painting".

Injection is typically **limited** to **15 – 20 turns**, ~60% efficiency

Estimate the maximum stored intensity based on the **SEEIST injector parameters** [1] and *Supernanogan* ECR source.

Injection is not thought to be space charge limited.





Parameter	Values		
	H^+	$^4He^{2+}$	$^{12}C^{6+}$
Linac Current [mA]	2.00	1.00	0.20
Injection Energy [MeV/u]	10	5	5
Orbital Period [μs]	0.49	0.69	0.69
Ions after 15 Turns [10^{10}]	**5.51**	**1.94**	**0.13**
Space Charge Tune Shift	-0.15	-0.02	< 0.01

[1] M. Vretenar *et al.*, J. Phys.: Conf. Ser. **2420** 012103 (2023)
[2] R. Taylor *et al.*, J. Phys.: Conf. Ser **2420** 012101 (2023)

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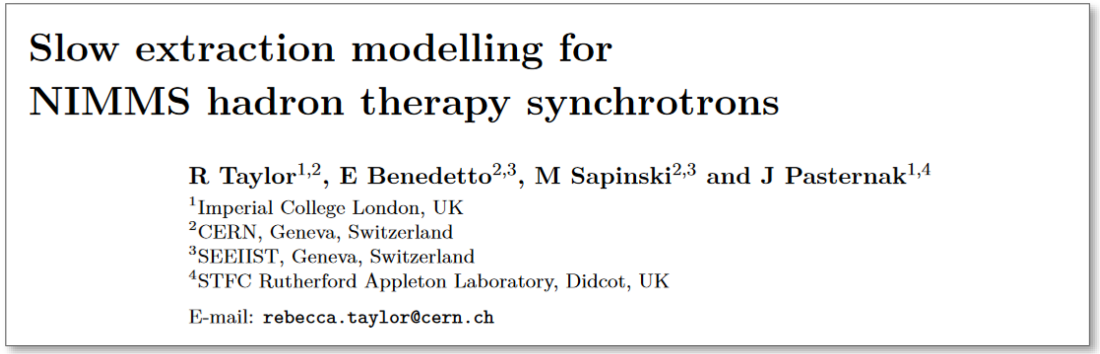
Beam Extraction

Work in Progress

Like NIMMS [1], we expect to use slow extraction using **RF knockout** (RFKO) at the **third order resonance**.

Extensive simulations have been carried out for the NIMMS and PIMMS (CNAO, MedAustron) designs [1].

Typical **extraction timescale** of ~100 ms to 1 s


Slow extraction modelling for NIMMS hadron therapy synchrotrons

R Taylor[1,2], E Benedetto[2,3], M Sapinski[2,3] and J Pasternak[1,4]
[1]Imperial College London, UK
[2]CERN, Geneva, Switzerland
[3]SEEIIST, Geneva, Switzerland
[4]STFC Rutherford Appleton Laboratory, Didcot, UK
E-mail: rebecca.taylor@cern.ch

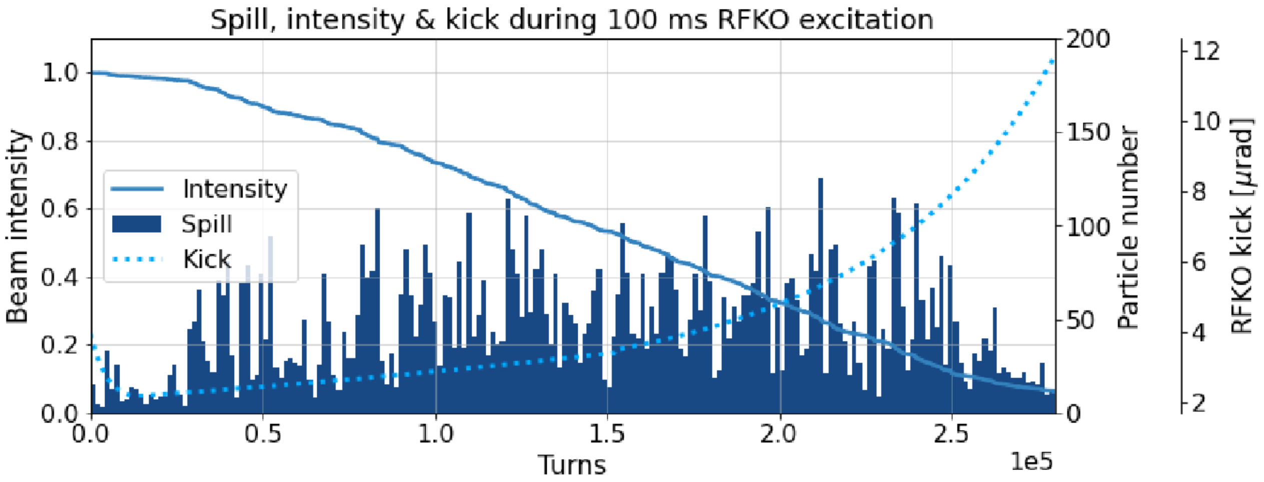


Figure: Simulation of 10^4 particles extracted via RFKO over 100 ms [1]

Conclusions

Thank you for listening

- A **preliminary synchrotron design** for ITRF WP3 has been established
- Layout is adapted from well-developed designs proposed by **CERN NIMMS**
- Synchrotron optics, beam energies and intensities are increasingly well defined
- Currently assessing **beam extraction** and corresponding dose rates

ITRF WP3 Contributors:

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- Karen Kirkby (Univ. Manchester)
- Elena Benedetto (CERN and SEEIST)

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Bonus Slides

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Documentation

Bonus Slide 1

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- Most **synchrotron documentation** held on the ITRF **TD server**
  \\fed.cclrc.ac.uk\Org\NLab\ASTeC-TDL\Projects\tdl-1272 ITRF\pa1 - CDR\acc - Accelerator

- Synchrotron **parameter sheet**
  1272-pa1-acc-para-0001-v0.3-synchrotron-parameters.xlsx

- MAD-X **lattice file**
  1272-pa1-acc-code-0001-v0.3-synchrotron-lattice.madx

- WP3 documentation
  \\fed.cclrc.ac.uk\Org\NLab\ASTeC-TDL\Projects\tdl-1272 ITRF\pa1 - CDR\wp3 - Conventional Technology