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ITRF WP3
Conventional Technologies

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ITRF 12-Month Review

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Introduction

ITRF WP3 Context

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- **ITRF WP3** aims to **compare** options based on **conventional technologies** against the baseline **LhARA** facility design
- This includes the evaluation of a **synchrotron**, with an **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

A Compact, Room Temperature Synchrotron

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Key Requirements:

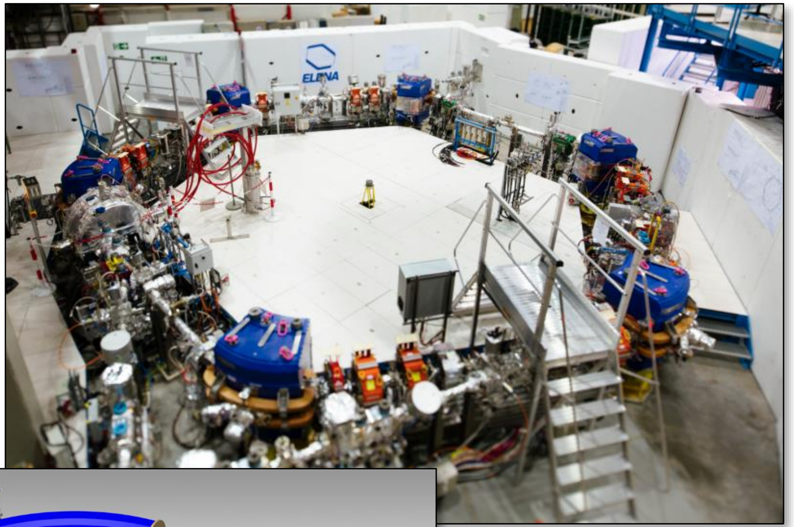
- Synchrotron is primarily designed for the **most likely radiotherapy ions** (H^+, $^4He^{2+}$ and $^{12}C^{6+}$), without excluding heavier ions in future
- Aim for stored intensities compatible with **FLASH regimes**, of order **10^{10} ions** per spill
- Machine fits within the **circumference** of the **LhARA FFA** (21.86 m) with **similar beam energies**
- Use accessible, conventional technologies e.g. **room temperature** magnets

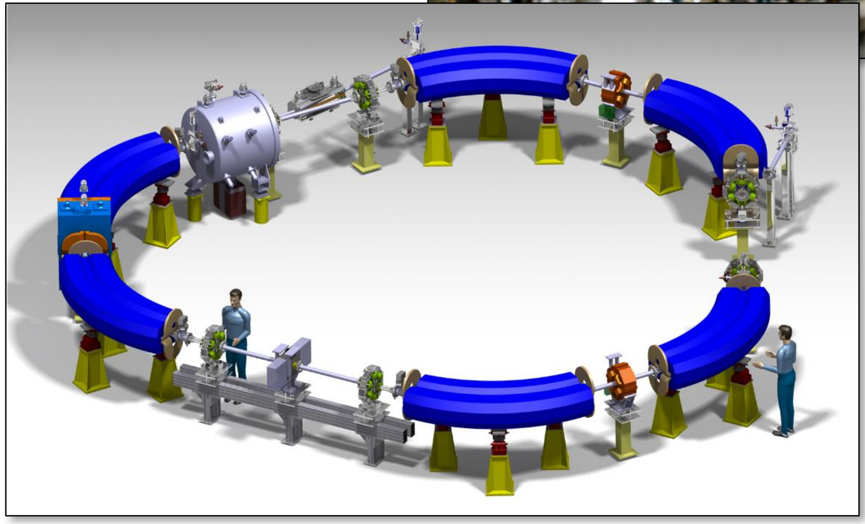
[1] H.X.Q. Norman *et al.*, Proc. IPAC '22, **THPOMS028** (2022)
[2] M. Vretenar *et al.*, J. Phys.: Conf. Ser. **2420** 012103 (2023)
[3] V. Chohan et al., Extra Low Energy Antiproton Ring (ELENA) and its Transfer Lines – Design Report, **CERN-2014-002** (2014)

Examples

CERN NIMMS and ELENA

- 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

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ITRF Synchrotron Design

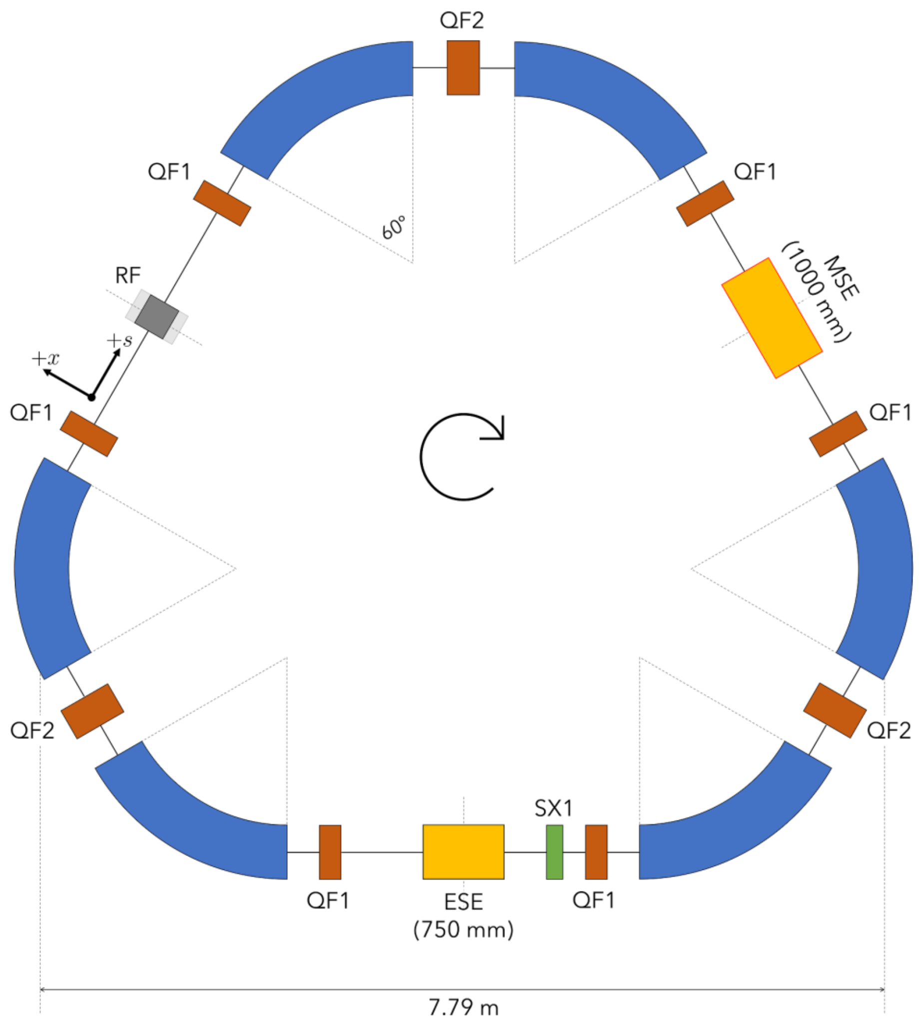
Overview

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

Small (~23.88 m circumference) synchrotron based on a **scaled** version of the **NIMMS $^{4}He^{2+}$ synchrotron** design [1]

- Ring comprised of three achromat lattice cells [2]
- Room temperature **1.50 T sector dipoles** allow $^{12}C^{6+}$ acceleration up to **83.5 MeV/u**
- **Dispersion-free straights** accommodate **injection**, **extraction** and RF hardware

Parameter	Value	
Dipole radius [m]	1.80	
Max. Dipole Field [T]	1.50	
Max. Beam Rigidity [T·m]	2.70	
Ion Species	H^{+}	$^{4}He^{2+}$, $^{12}C^{6+}$
Max. Beam Energy [MeV/u]	105.5†	83.5
Orbital Frequency [MHz]	5.50	4.97



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

ITRF Synchrotron Design

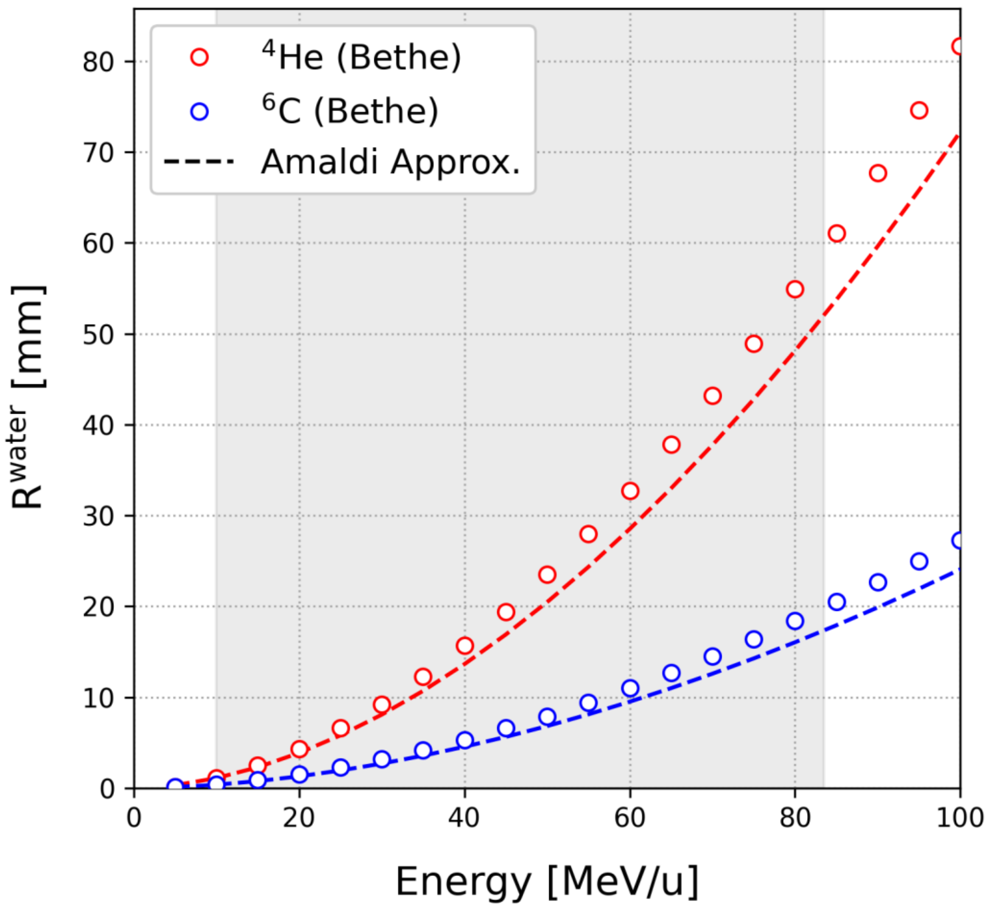
Choice of Beam Energy

Making the synchrotron slightly larger than the LhARA FFA* facilitates **higher $^{12}C^{6+}$ extraction energies**

- **Synchrotron**: 83.5 MeV/u
- **LhARA FFA**: 33.4 MeV/u

Higher-energy synchrotron has now been adopted as the **baseline WP3** machine design

Extraction energy chosen to provide a maximum **irradiation depth** of ~**20 mm**

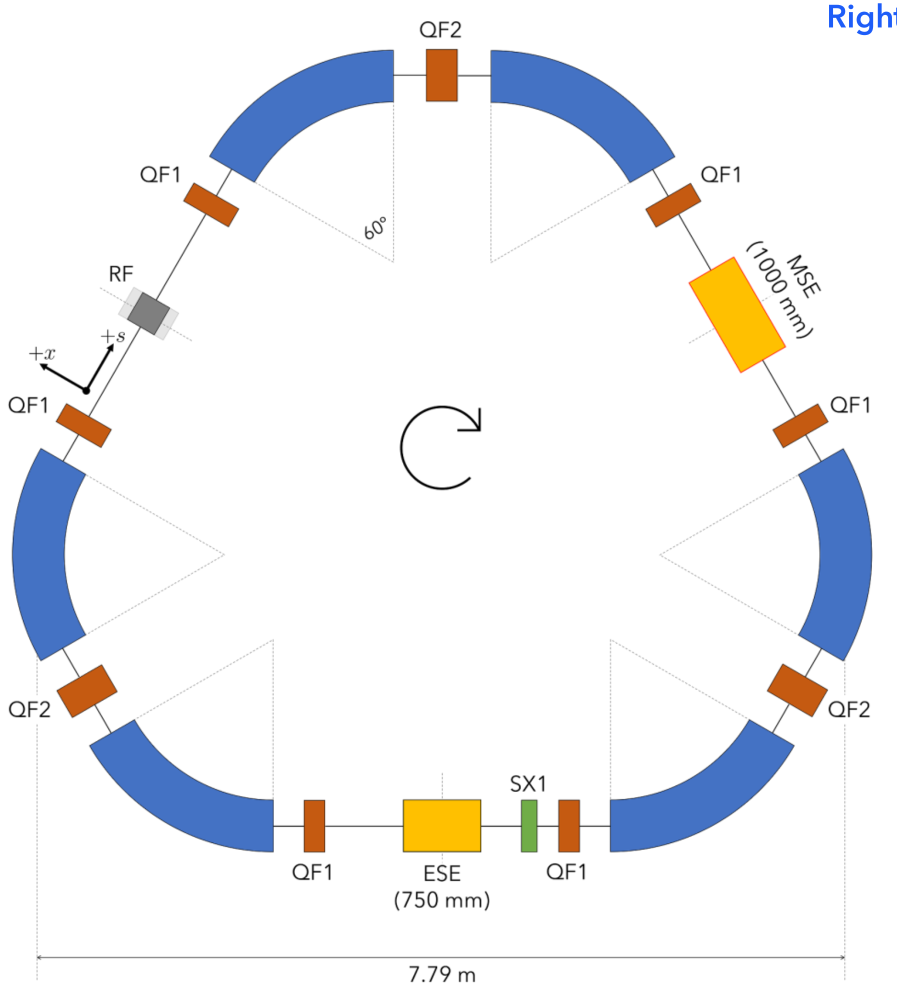


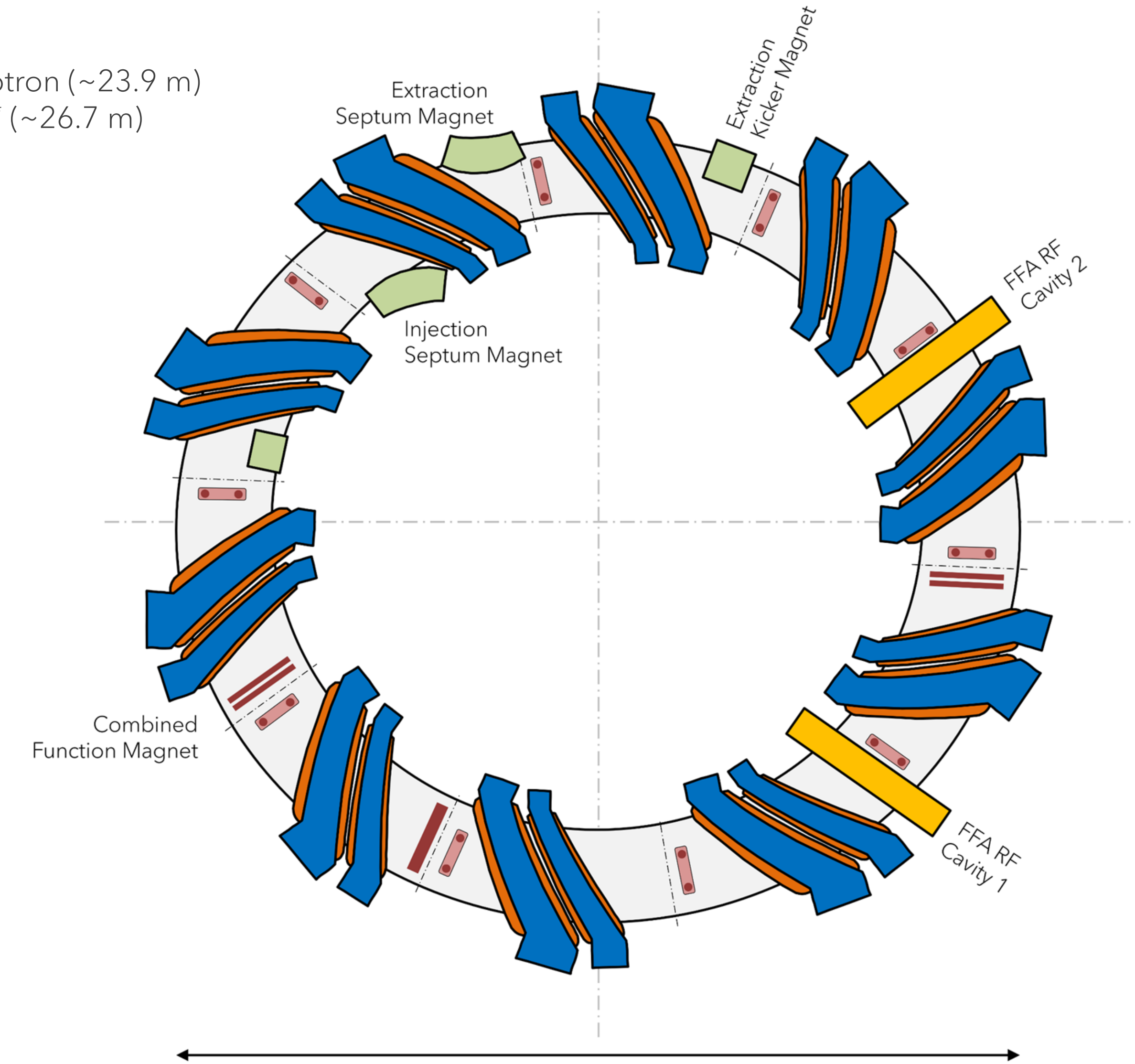
** Original pre-CDR FFA design, circumference ~21.9 m*

Machine Footprints

Approximately to Scale

Left: ITRF WP3 synchrotron (~23.9 m)
Right: LhARA FFA* (~26.7 m)





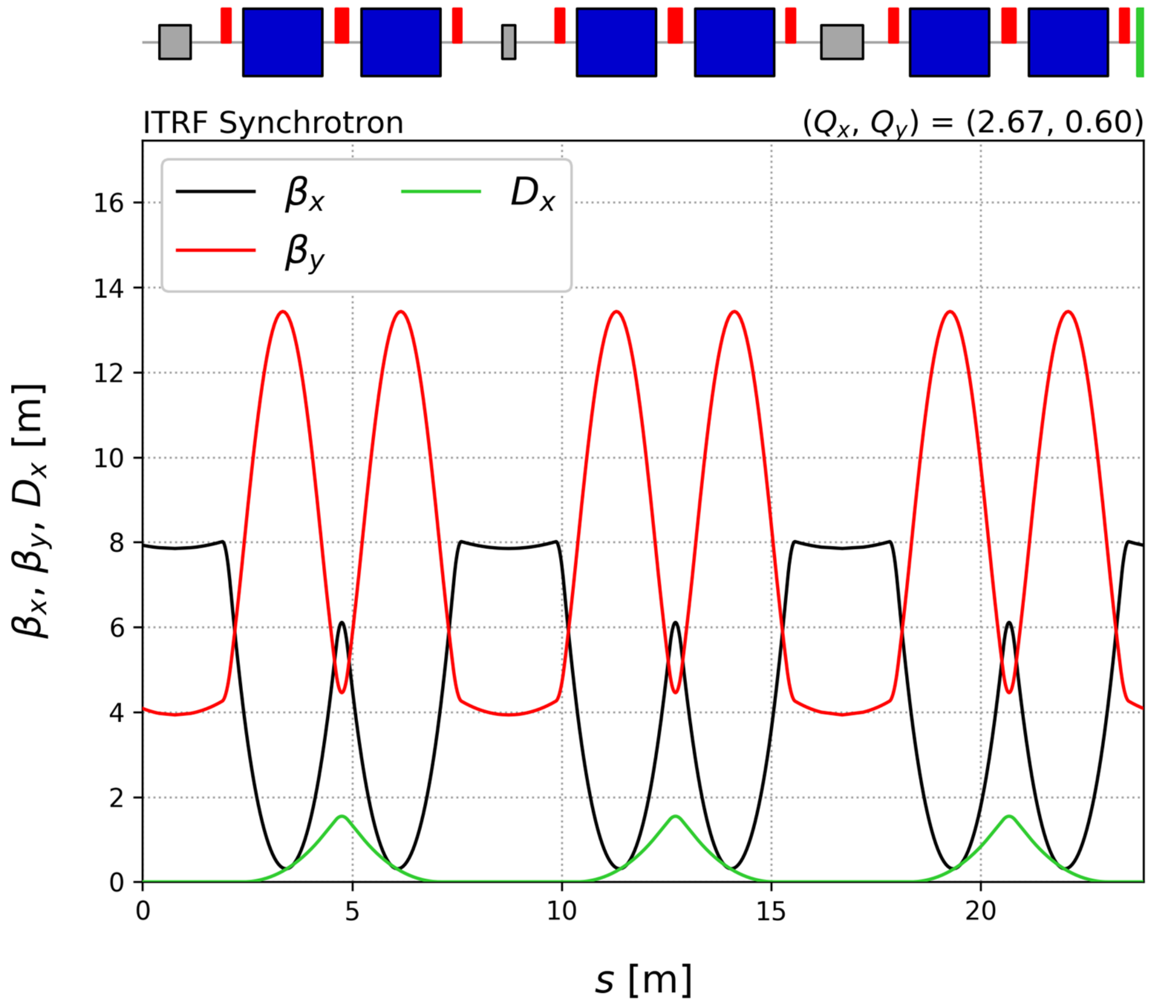
ITRF Synchrotron Design

Beam Optics

The synchrotron design was optimised to **maximise** the accessible range of **working points**

Optics are tuned near a **third-order resonance** (Q_x = 2.66) for compatibility with slow, **resonant beam extraction** [1]

Parameter	Value
Optics Functions	
Max. β_x [m]	8.01
Max. β_y [m]	13.4
Max. D_x [m]	1.55
Working Point	
Tune Q_x, Q_y	2.66, 0.60
Chromaticity Q'_x, Q'_y	-3.82, -3.62



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)

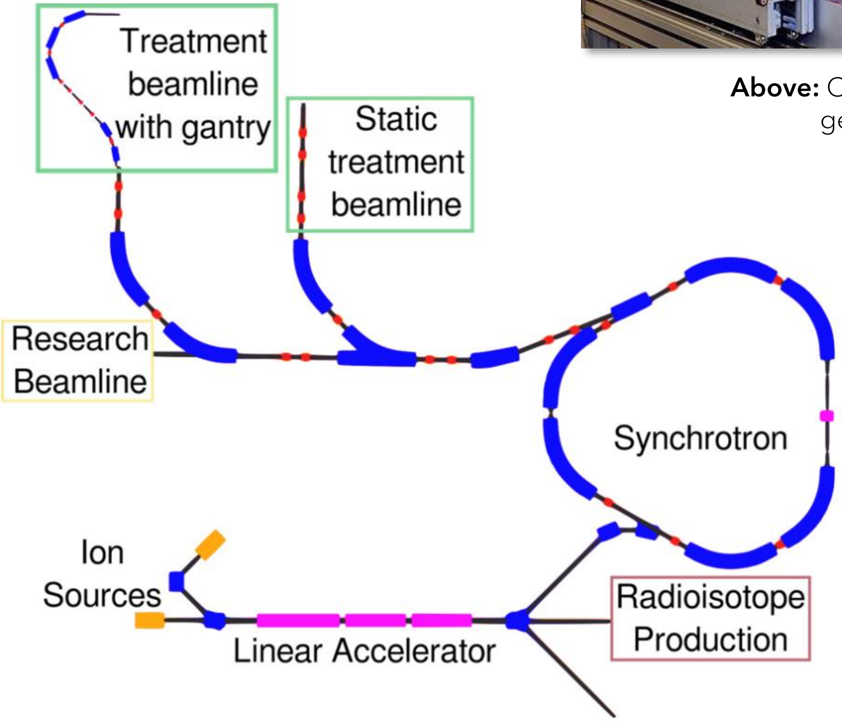
NIMMS propose [1] a **conventional injector** chain based on **CERN Linac 4**

- 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+}



Left: 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)

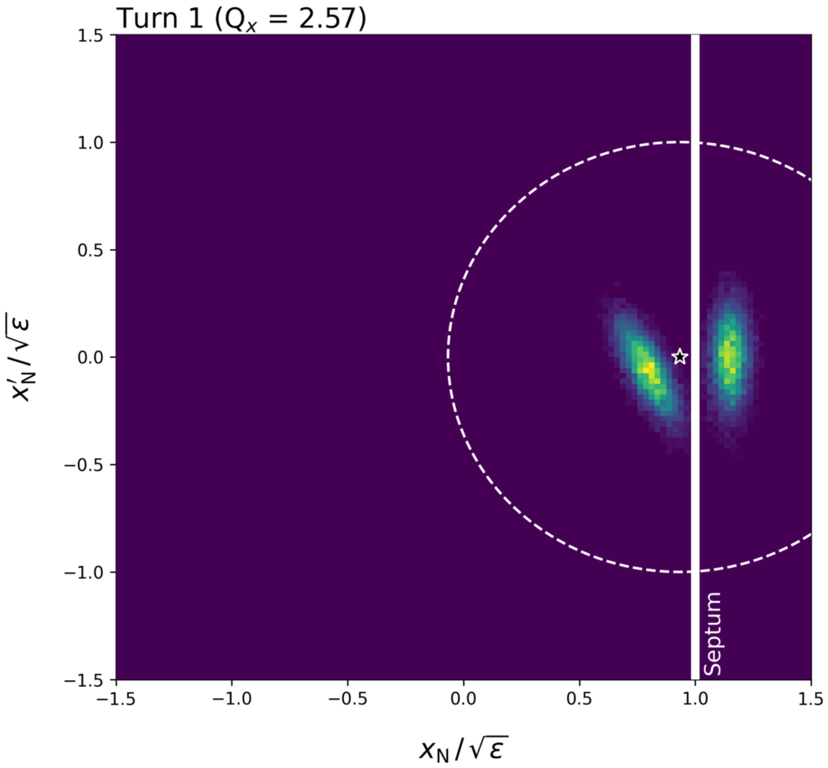
Beam Injection

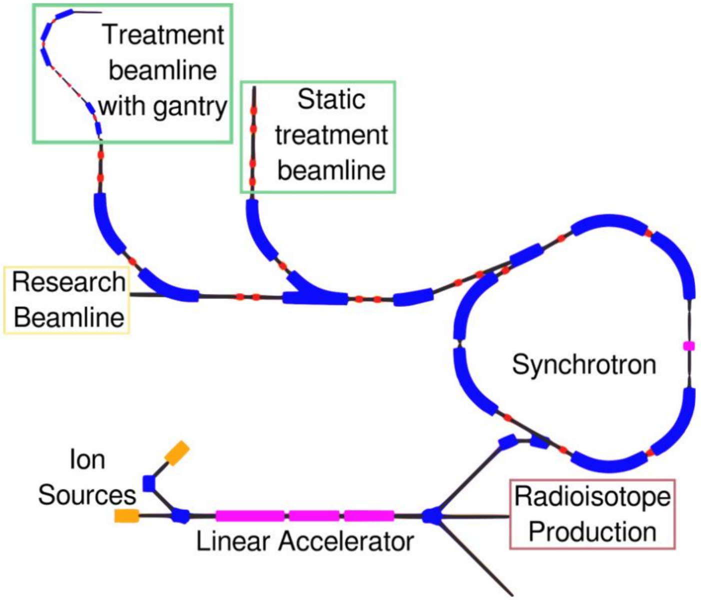
Multi-Turn Injection

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

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

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





Parameter	Values		
	H^+	$^4He^{2+}$	$^{12}C^{6+}$
Linac Current [mA]	2.0	1.0	0.2
Injection Energy [MeV/u]	10	5	5
Orbital Period [MHz]	1.82	1.29	1.29
Ions after 15 Turns [10^{10}]	**6.19**	**2.18**	**0.15**
Max. Space Charge Tune Shift	-0.18	-0.02	< 0.01

Beam Extraction

Particle Tracking Simulations

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

Like NIMMS [1], we expect to use **slow resonant extraction** using **RF knockout** at the third-order resonance

Extensive extraction simulations have been carried out for the CERN PIMMS designs (e.g. CNAO, MedAustron) [2]

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

Extraction scheme for the WP3 synchrotron is being **validated** using **MAD-X** particle tracking:

- Locations of extraction hardware
- Preliminary specifications for septa

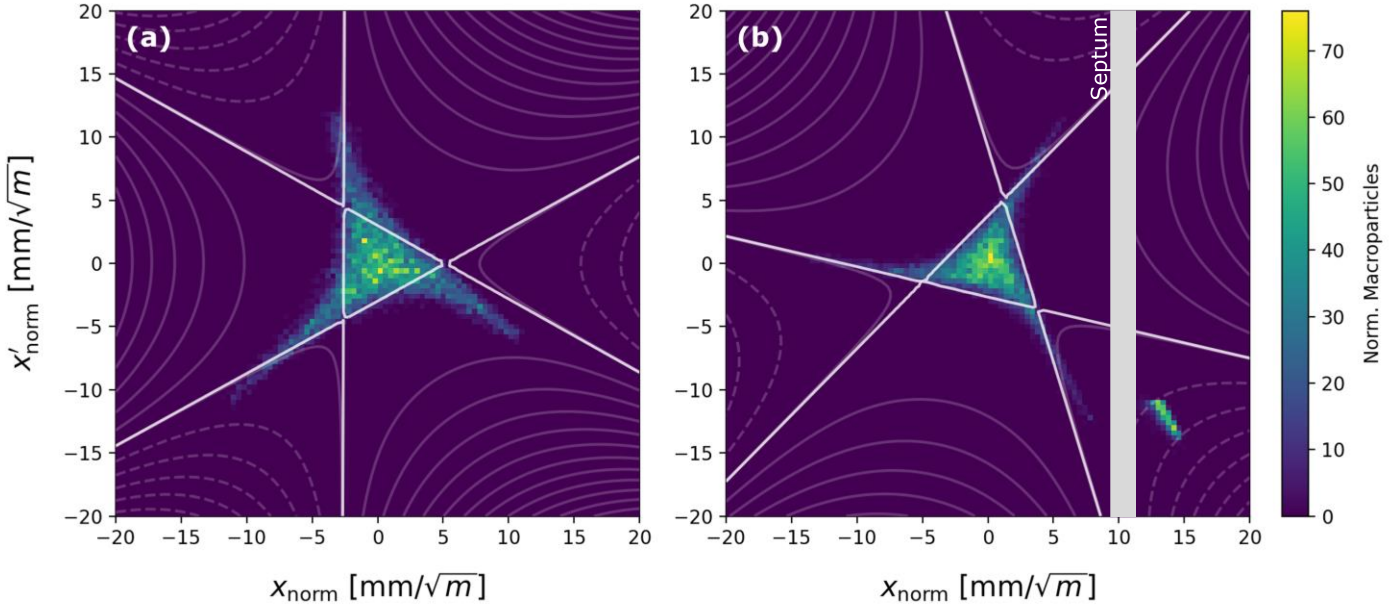


Figure: Normalised beam phase space **(a)** after excitation of the resonance, and **(b)** with "extracted" ions at the magnetic septum

Dose Rates

Preliminary Estimates

[1] H.L. Owen *et al.*, *Contemporary Physics* **55:2**, 55-74 (2014)

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Indicative dose rates were calculated [1] for a **9 cm^3 irradiation volume**:

- 3 x 3 cm field size
- Depth from 0 – 1 cm

We assume a **uniform** irradiation using a **Spread-Out Bragg Peak** (SOBP) approach, and neglect lateral scattering.

Dose rate estimated from the energy deposited during a typical **100 ms slow extraction**.

Parameter	**Value**		
	H^+	$^4He^{2+}$	$^{12}C^{6+}$
Ions per Spill [10^{10}]	5.0	2.0	0.15
Median Energy [MeV/u]	23.1	23.1	42.2
Dose per Spill [Gy]	20.5	32.8	13.5
Instantaneous Dose Rate [Gy/s]	**205**	**328**	**135**
Average Dose Rate [Gy/s]	20.5	32.8	13.5

Equivalent LhARA Calculation

- 10^9 protons per pulse
  7 ns bunches at 10 Hz
- Instantaneous : **6×10^7 Gy/s**
  Average: **4.1 Gy/s**

Slides from
Karen Kirkby

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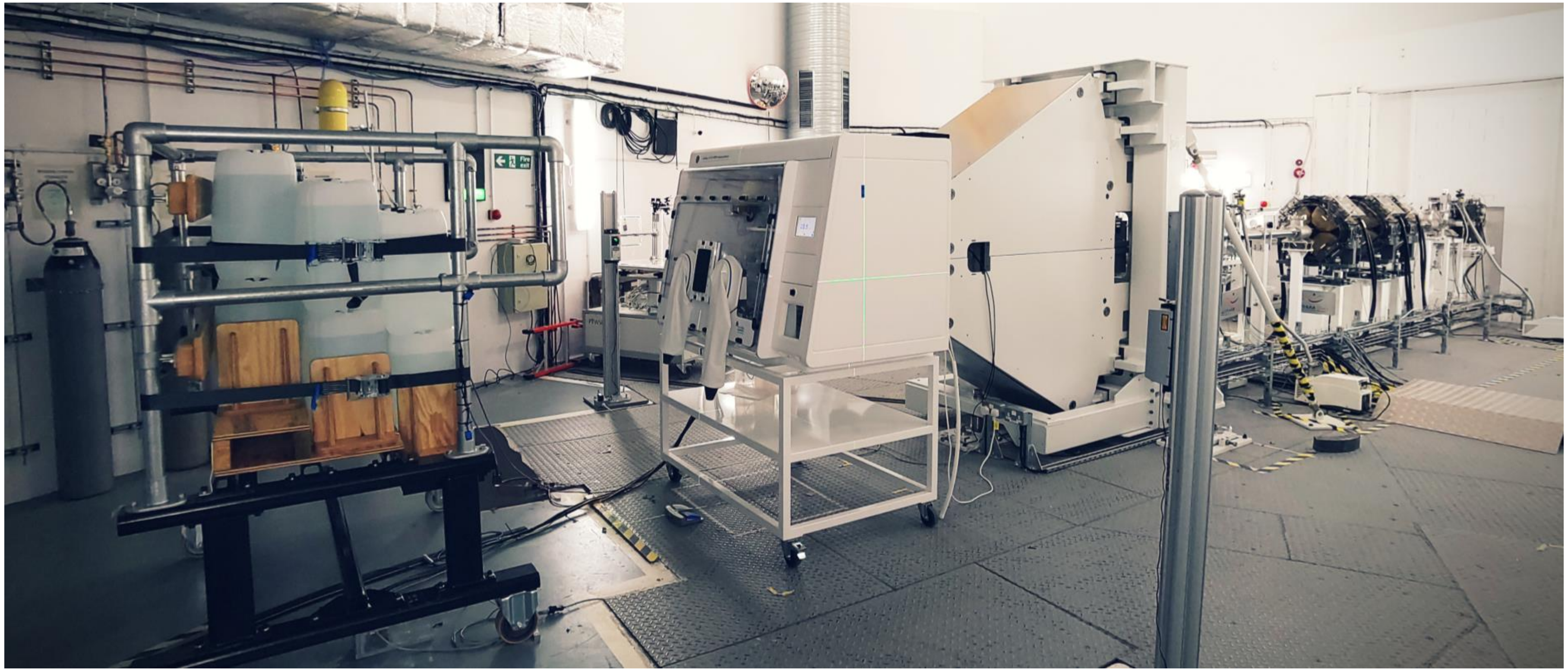
End Stations

Research Room at The Christie, Manchester

The Christie Charity

MANCHESTER 1824 The University of Manchester



Prof. Ranald Mackay

Dr Helena Kondryn

End Stations

Research Room at The Christie, Manchester

The Christie Charity

MANCHESTER 1824
The University of Manchester

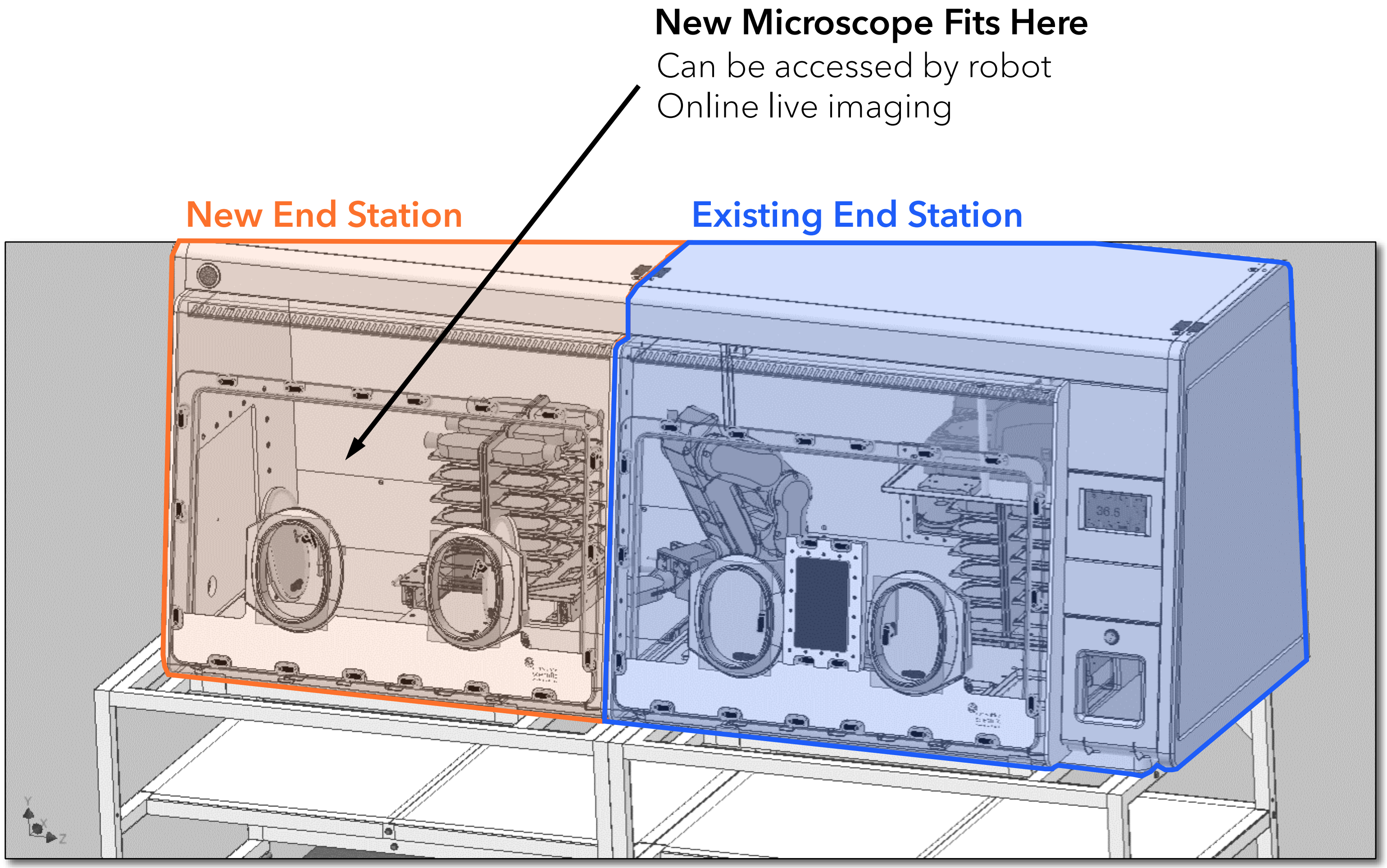
Research Room End Station

- **O_2**: 0.1% - ambient
- **CO_2**: 0% - 20%
- **Temperature:** Ambient +4 °C – 45 °C
- **Humidity:** Ambient – 100 %
- **Scanning Area:** 20 x 20 cm
- **6-Axis Robot:** 30s between samples
- **Hotel:** 36 samples (54/night)
- Automated liquid handling for 96-well plates
- Scattered dose to hotel at worst 1.27 mGy/Gy

New End Station

Working with Don Whitley Scientific

- **Now fully funded**
- **Second Hotel of Samples**
  Increased throughput
- **Cooled stage**
  DNA repair
  FLASH studies
- **Online microscopy**
- **Utilises same robot**
- **And much more…**



Conclusions

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- A **baseline synchrotron option** for ITRF WP3 has been established, based on designs proposed by **CERN NIMMS**
- The synchrotron achieves a **higher $^{12}C^{6+}$ extraction energy** than the LhARA FFA (83.5 MeV/u)
- MAD-X **particle tracking simulations** are being developed to explore and refine the scheme for **slow extraction**
- Instantaneous **dose rates** expected to be of order ~**100 Gy/s**

WP3 REPORT

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Bonus Slides

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Christie Research Room

Video

https://www.youtube.com/watch?v=j2QR4PQvael