

Beam stacking and RF knockout in Fixed Field Accelerators

Carl Jolly, D.J.Kelliher, J.-B. Lagrange, A. P. Letchford, S. Machida,
D.W. Posthuma de Boer, C.T. Rogers, A. Seville

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ISIS Neutron and
Muon Source



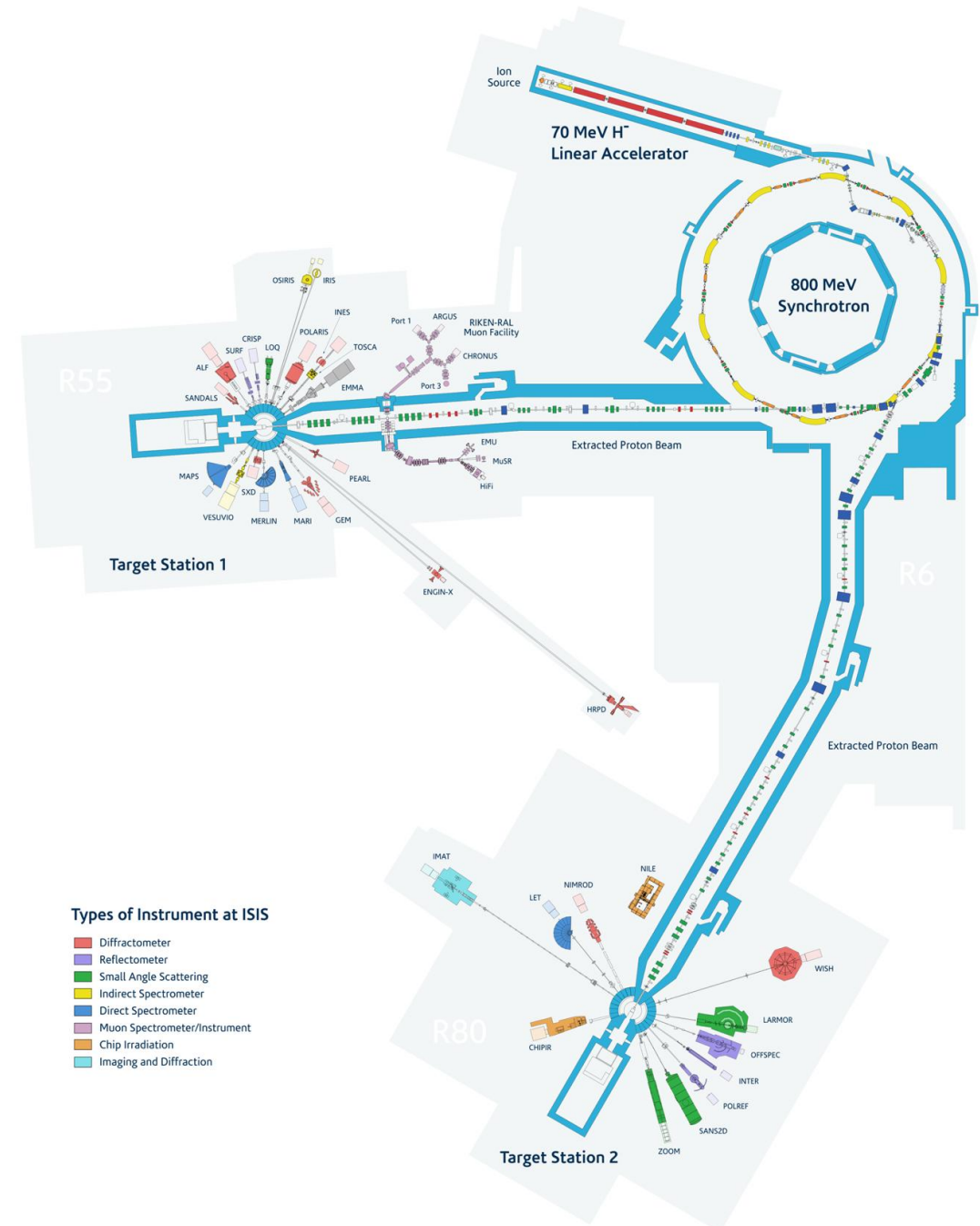
Contents

- ISIS Neutron and Muon Source and ISIS-II
- What are FFAs?
- Beam stacking
 - KURNS experiment to demonstrate beam stacking.
- RF knockout during stacking and experiments at ISIS.

ISIS and ISIS-II

- ISIS is a pulsed Neutron and Muon source at the Rutherford Appleton Laboratory.
- The ISIS accelerator is a 50Hz rapid cycling synchrotron (RCS) built in **1984**.

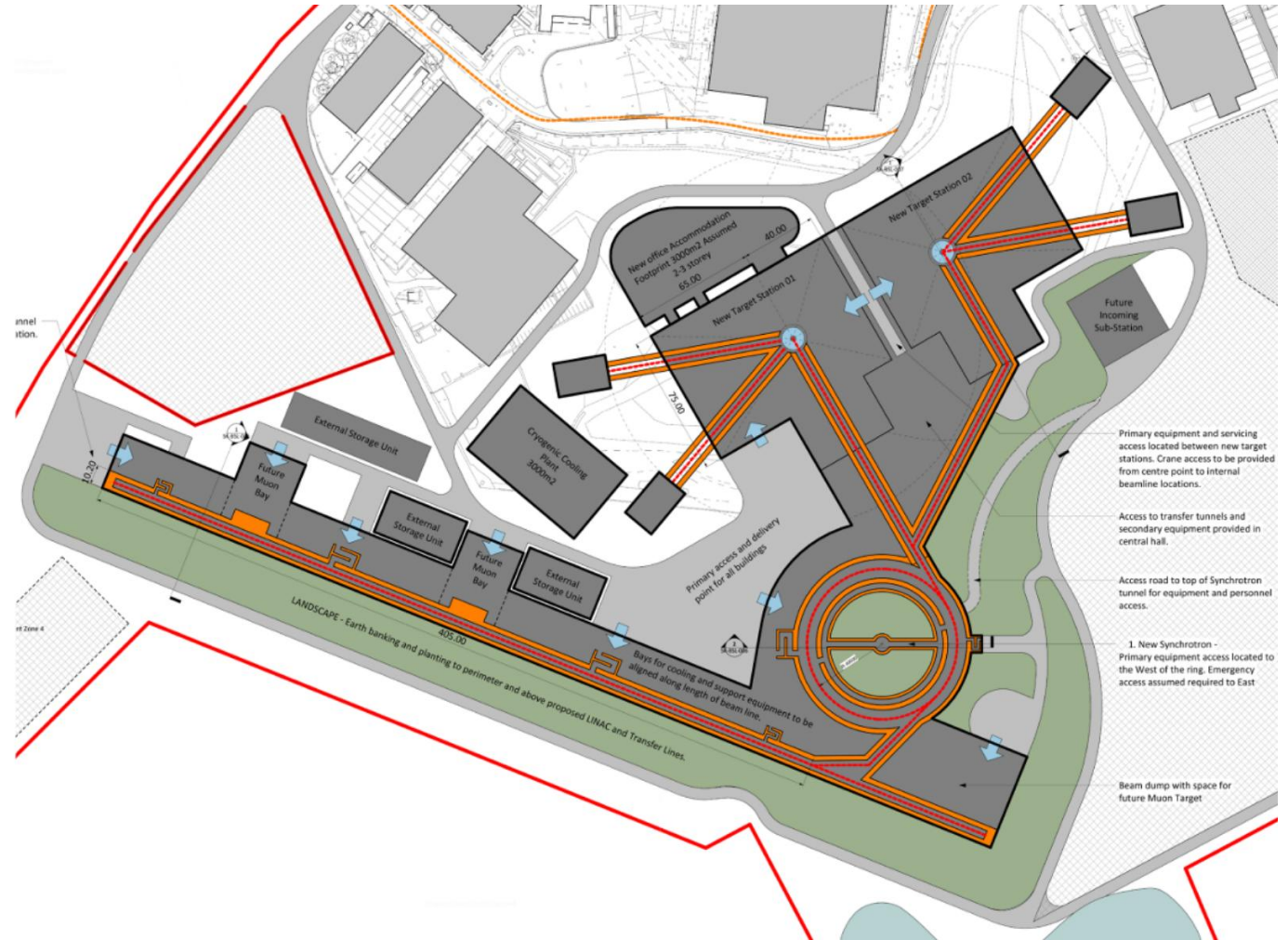
ISIS parameters	Value
Circumference	163 m
Energy Range	70 – 800 MeV
Repetition Rate	50 Hz
Charge	2.5 – 3.0e13 protons-per-pulse



ISIS and ISIS-II

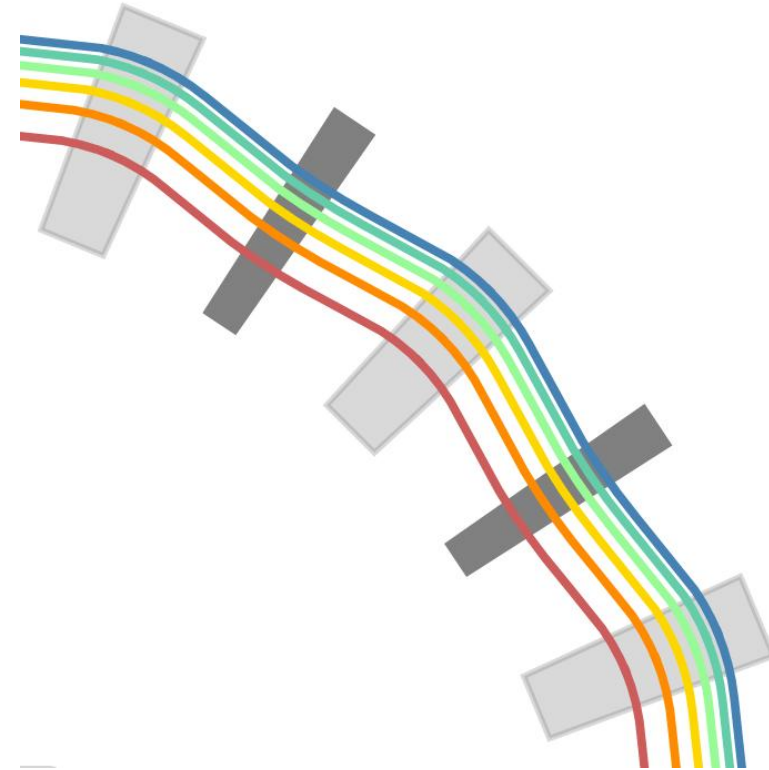
More beam power = more neutrons

Various options for the proton accelerator are under consideration including an RCS, Accumulator ring or even an FFA.



FFAs

- **Fixed Field alternating gradient Accelerator**
→ FFA.
- In an FFA the bending field is fixed.
- The closed orbit moves to a **higher radius with increasing energy**.
- The magnets are generally a combined function element.



From: Topp-Mugglestone, M. E. (2024).
Scaling fixed field accelerators: theory and
modelling of horizontal- and vertical-
excursion accelerators [PhD thesis]

FFAs for spallation neutron sources

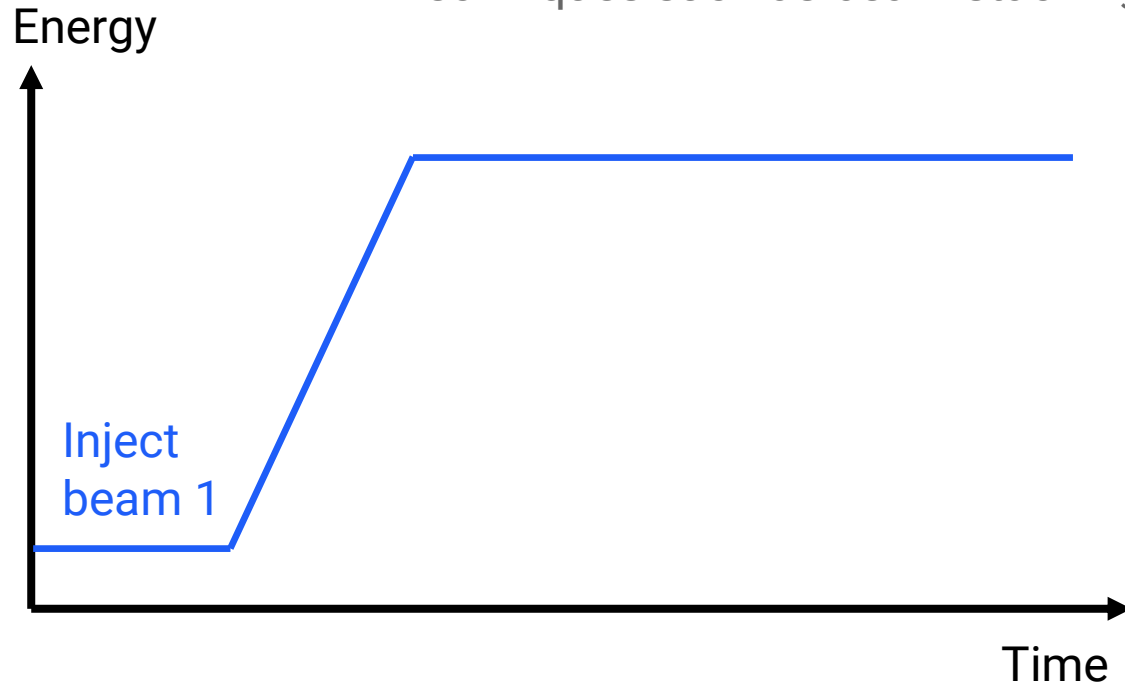
- The goal of the accelerator in a spallation neutron source is to deliver as **much beam power as possible with the specified time structure** – typically 10s of Hz.
 - Beam stacking allows an FFA to accumulate more beam in a single pulse.
 - High power beam → low loss operation.
 - Cost/power efficiency.
 - More sustainable?

Beam Stacking

- The fixed field of an FFA allows you much more freedom to manipulate the beam.
 - Techniques such as beam stacking become possible.

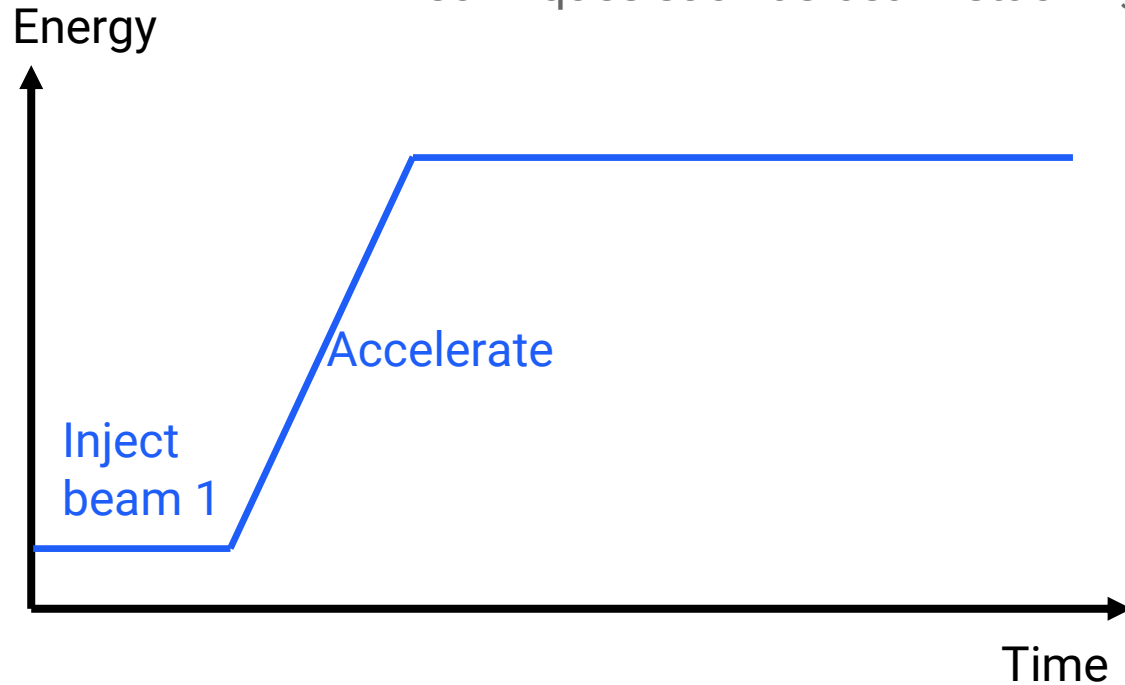
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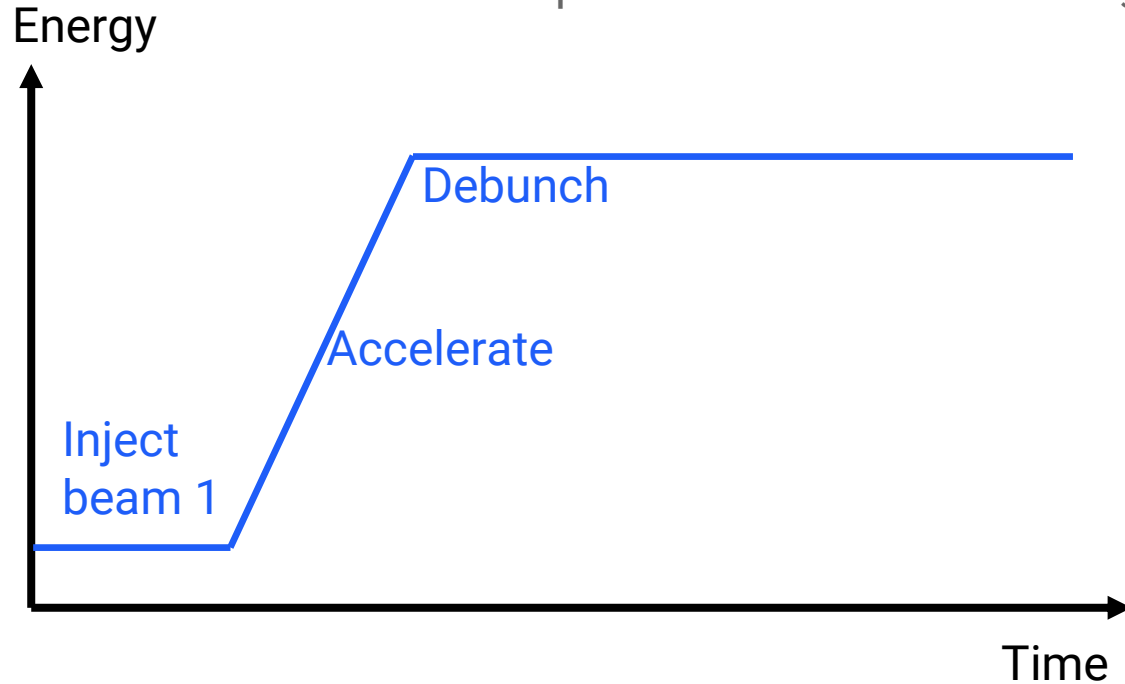
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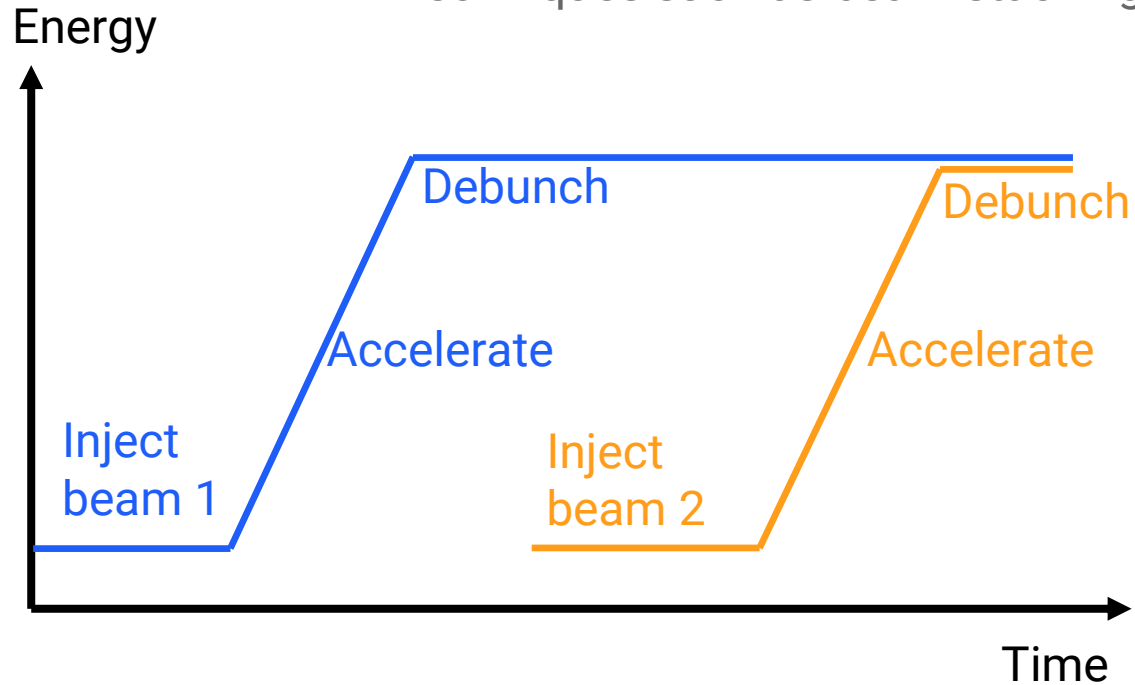
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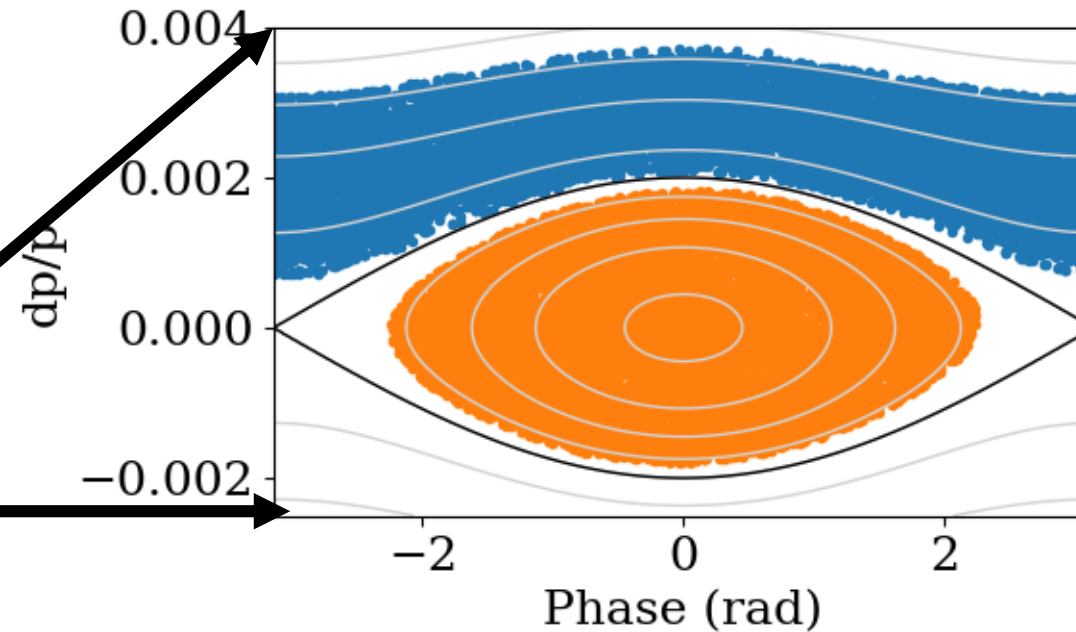
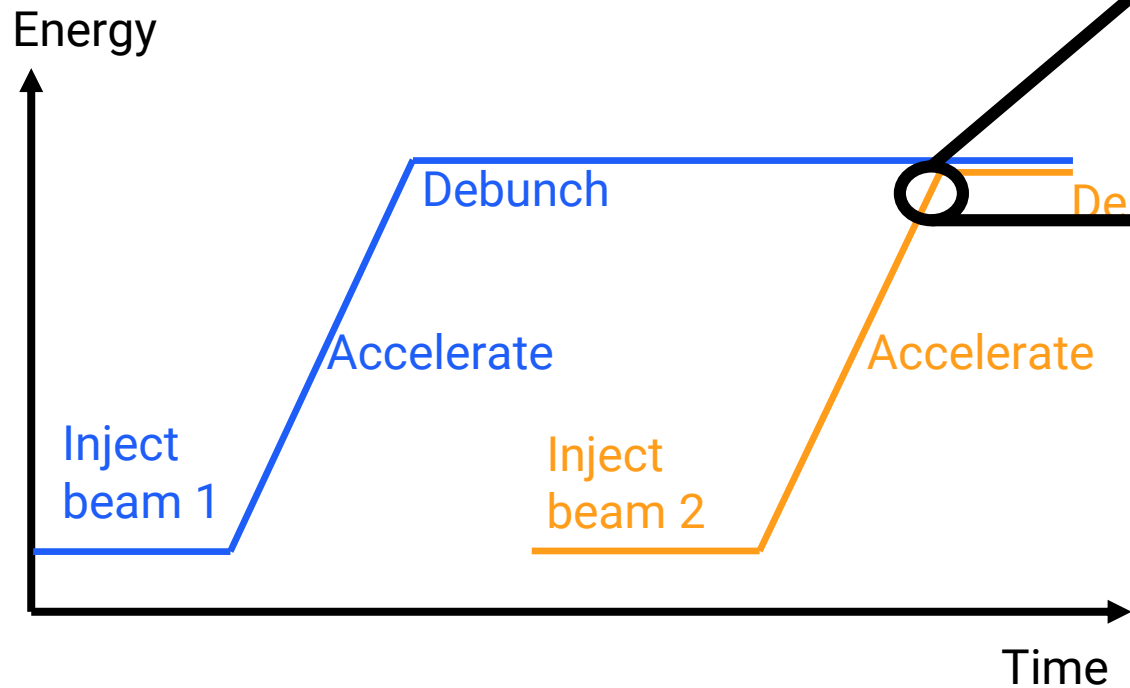


Beam Stacking

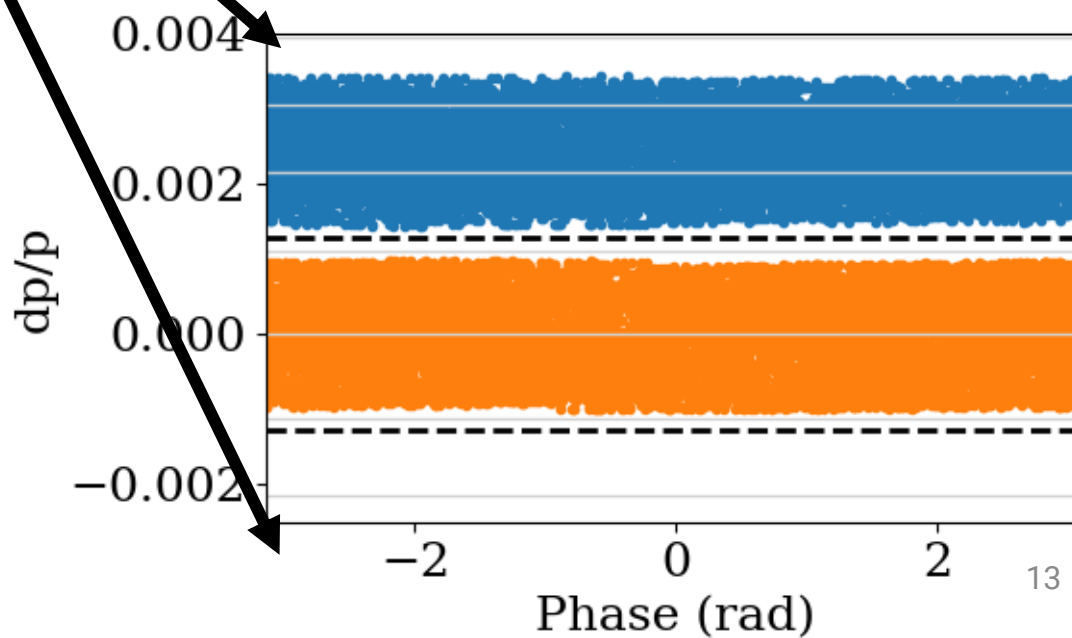
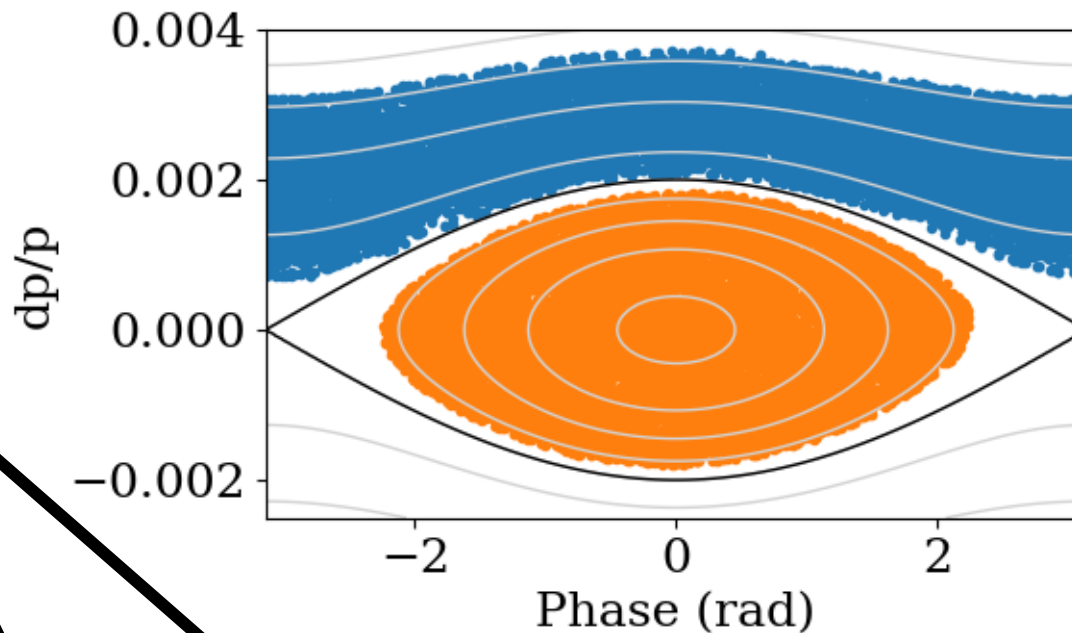
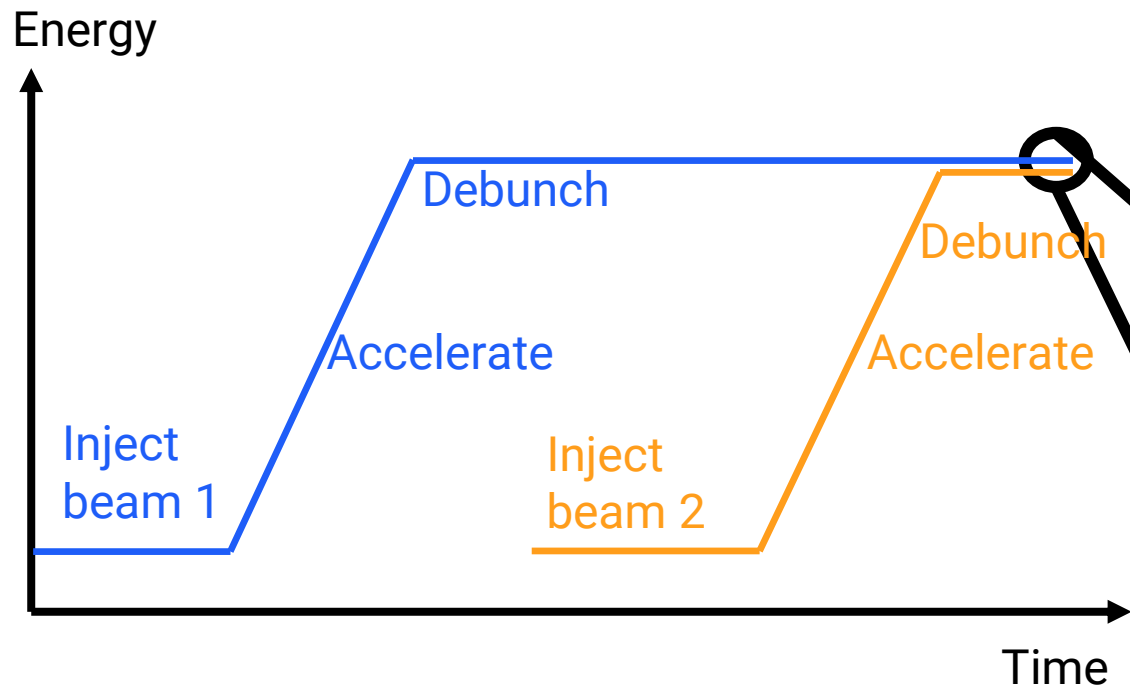
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Beam Stacking

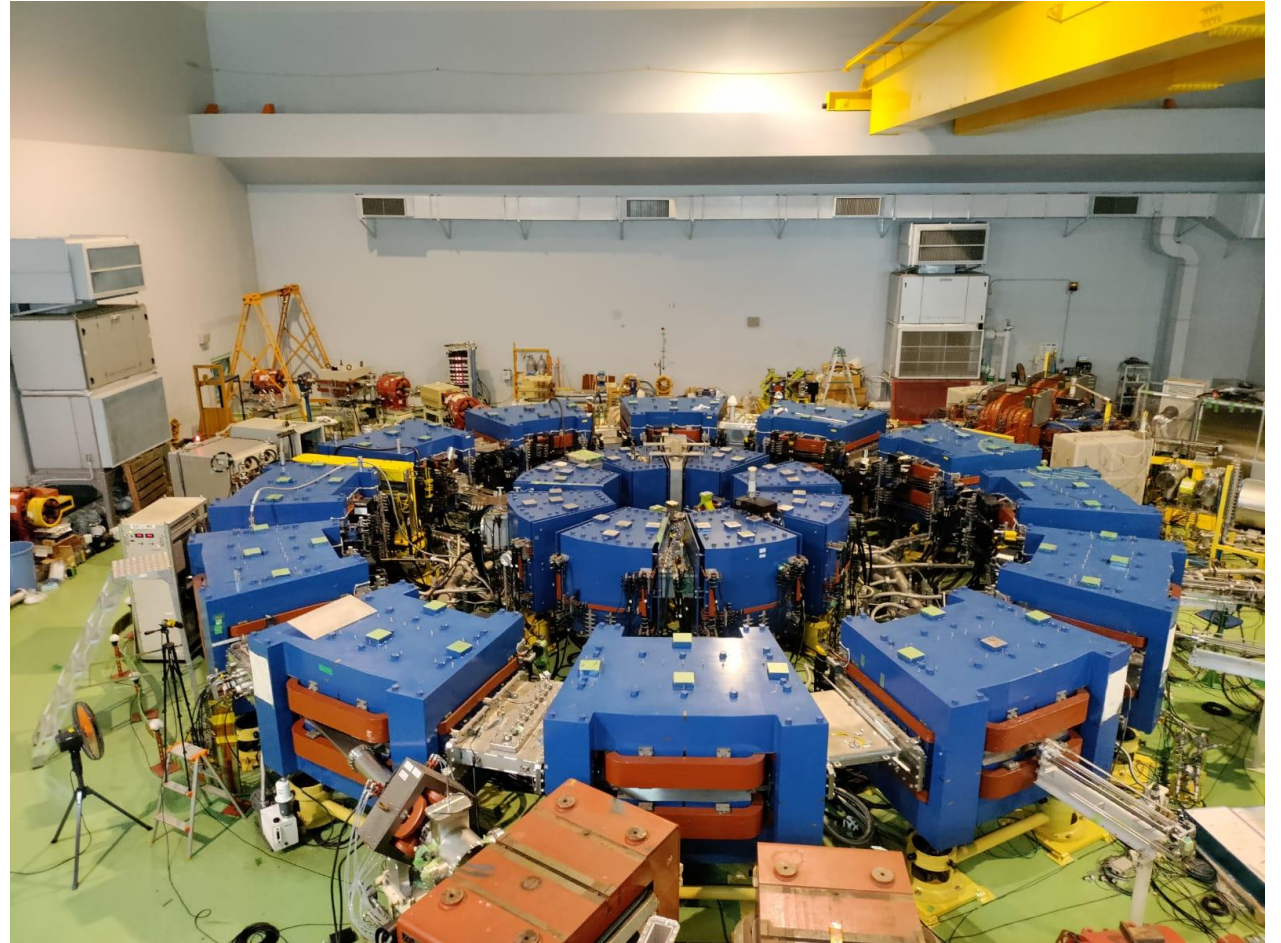


Beam Stacking

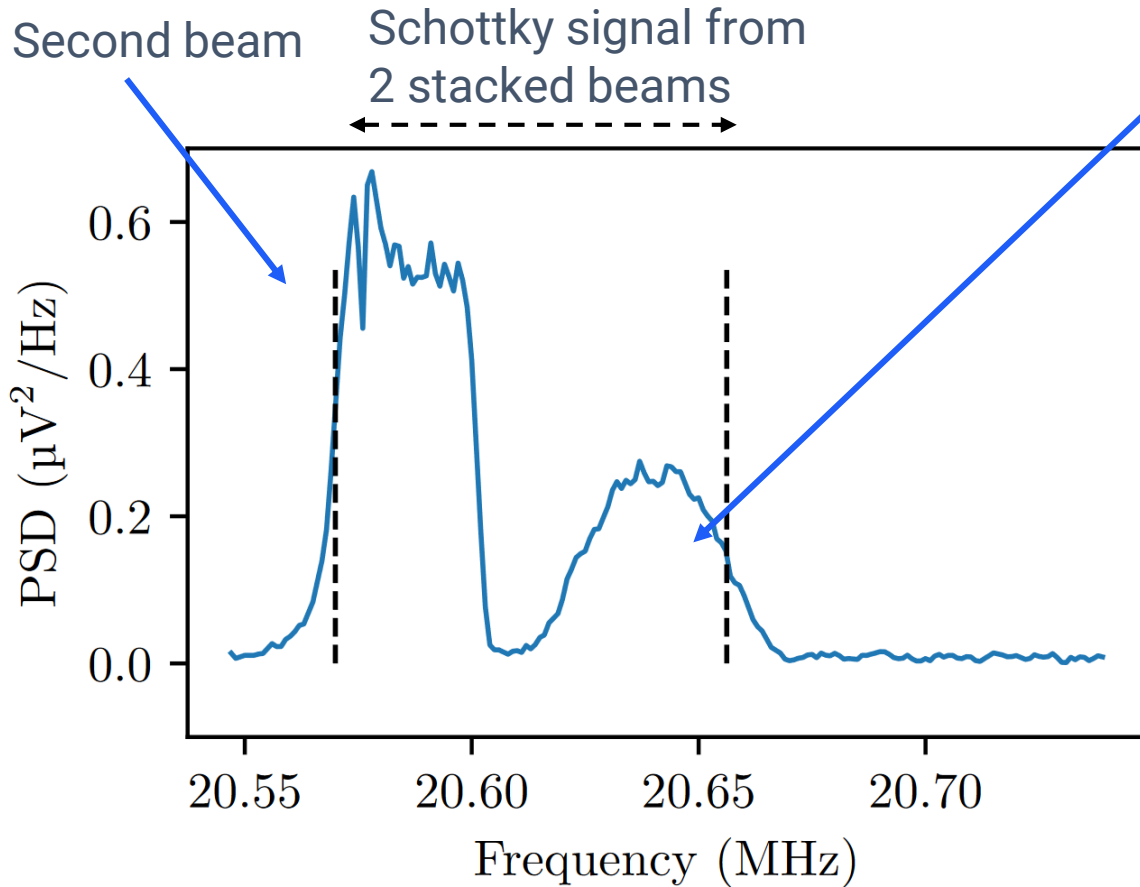


KURNS FFA

- Located near Osaka in Japan.
 - The KURNS FFA was the proton driver for a prototype accelerator driven nuclear reactor.
- Now (temporarily?) shutdown.
 - Our beam stacking experiment was one of its final runs!



Demonstration of beam stacking at KURNS FFA in 2023



First beam, the area of the peak is smaller as some of the beam has been lost.

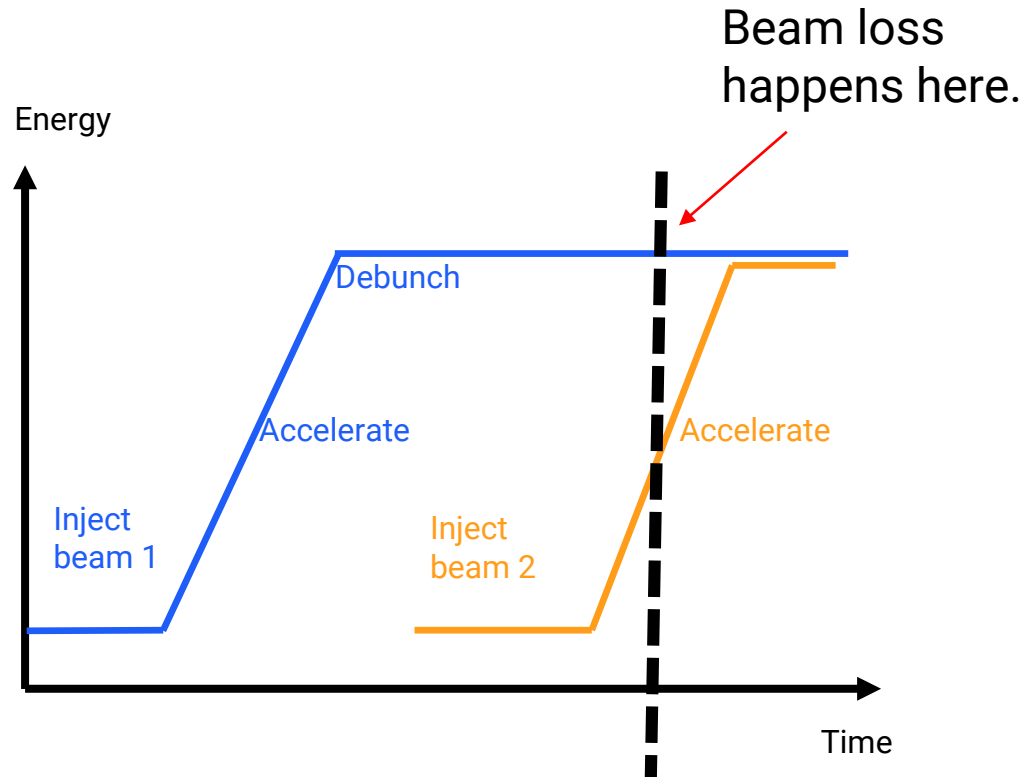
Results published in Physical review accelerators and beams here:

T. Uesugi et al. - [Beam Stacking Experiment at a Fixed Field Alternating Gradient Accelerator](#)

Beam stacking was first demonstrated at the MURA FFA in the 1960s

We attempted to make a more systematic measurement at KURNS.

Beam loss during stacking



- Investigating the cause of beam loss:
 - The loss only happened in **beam 1** → so likely not caused by some transverse effect/aperture limitation.
 - The loss still happened even if the **beam 2 RF bucket** was empty → implied that the loss was related to the RF.

What caused the beam loss? → RF knockout

- In a scaling FFA, the orbit is dispersive everywhere in the ring.

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- In a scaling FFA, the orbit is dispersive everywhere in the ring.
- Every time the particle gains energy from the cavity, the equilibrium orbit moves because of the finite dispersion.
→ Equivalent to an **instantaneous, horizontal displacement** when passing the cavity.

$$\delta_x = -\frac{D_x}{1 + \gamma} \frac{\delta E}{E}$$

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- In a scaling FFA, the orbit is dispersive everywhere in the ring.
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$$\delta_x = -\frac{D_x}{1 + \gamma} \frac{\delta E}{E}$$

- If these displacements **synchronise with the horizontal tune** then they could build up turn by turn.

RF knockout mechanism

$$\frac{d^2 x}{dt^2} + \omega_\beta^2 x =$$

ω_β = Horizontal tune frequency

x = Horizontal position

t = time

RF knockout mechanism

$$\frac{d^2 x}{dt^2} + \omega_\beta^2 x = A \sum_n e^{i(n\omega_{\text{rev}} + \omega_{RF})t + i\phi}$$

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RF knockout mechanism

$$\frac{d^2 x}{dt^2} + \omega_\beta^2 x = A \sum_n e^{i(n\omega_{\text{rev}} + \omega_{\text{RF}})t + i\phi}$$

The RF knockout resonance condition is:

$$\pm\omega_\beta = \omega_{\text{RF}} + n\omega_{\text{rev}}$$

ω_β = Horizontal tune frequency

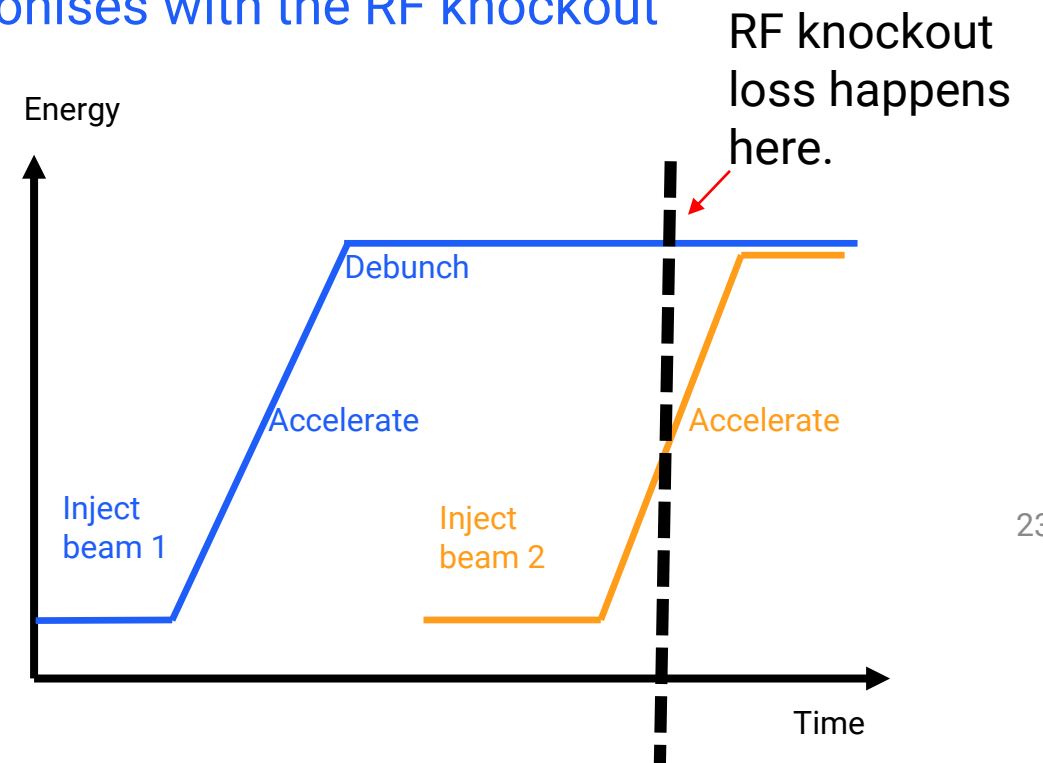
x = Horizontal position

t = time

A = constant

To recap

- Beam stacking allows an FFA to accumulate more beam and deliver to the target.
- But the beam stacking RF program can cause beam loss through RF knockout.
- RF knockout happens when the horizontal tune synchronises with the RF knockout displacements.
 - The displacements build up like an integer resonance.



Mitigating RF knockout

How can we prevent RF knockout driven beam loss?

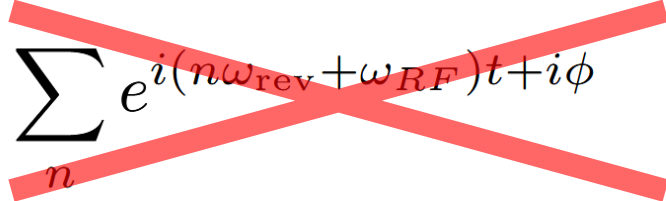
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- How can we remove the driving force?
 - Reduce the RF voltage or accelerate faster.

How can we prevent RF knockout driven beam loss?

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All depends on removing the driving force from RF knockout.

- How can we remove the driving force?
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 - Cancel out the RF knockout displacement with down stream cavities (local cancellation).

How can we prevent RF knockout driven beam loss?

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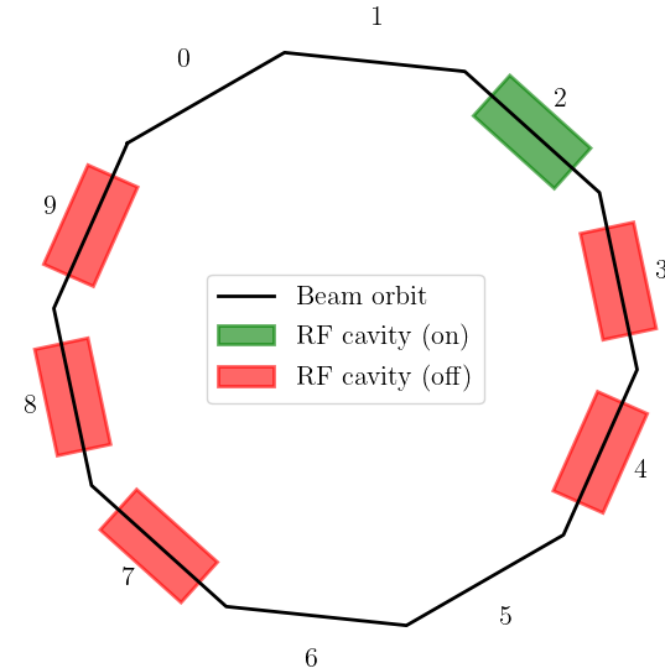
- How can we remove the driving force?
 - Reduce the RF voltage or accelerate faster.
 - Cancel out the RF knockout displacement with down stream cavities (local cancellation).
 - Leverage the properties of the RF knockout process to cancel out the beam oscillation (global cancellation).

Experiments at ISIS

- ISIS is of course a synchrotron and not an FFA.
 - We cannot perform “proper” beam stacking in ISIS but we can imitate a beam stacking RF program using “storage ring mode”.
 - Allows for the investigation of RF knockout mitigation methods without an FFA.
 - ... It turns out that the ISIS RF cavity layout is very convenient for testing RF knockout.

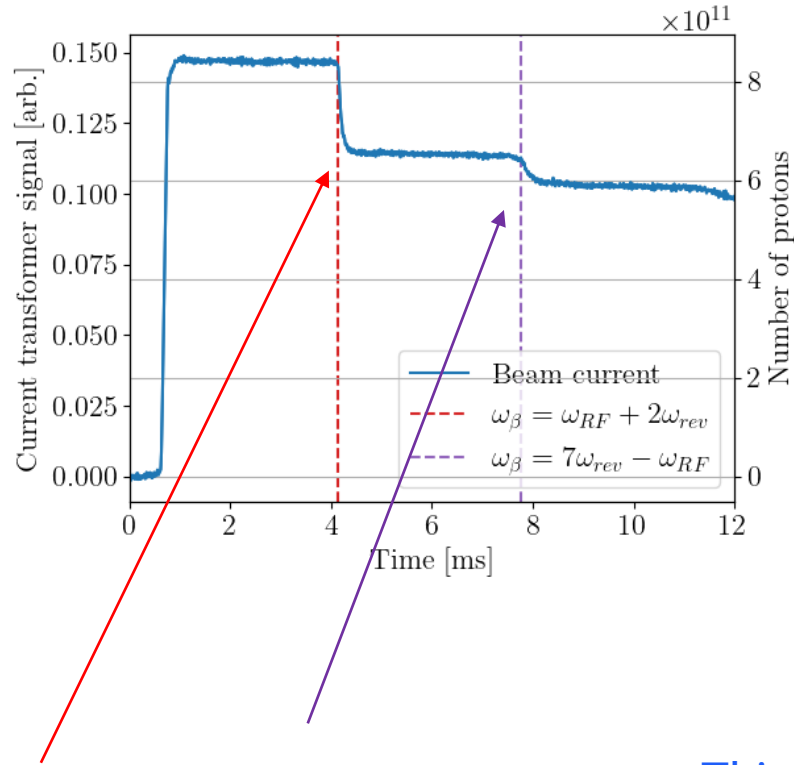
No mitigation case

ISIS fundamental RF cavity layout



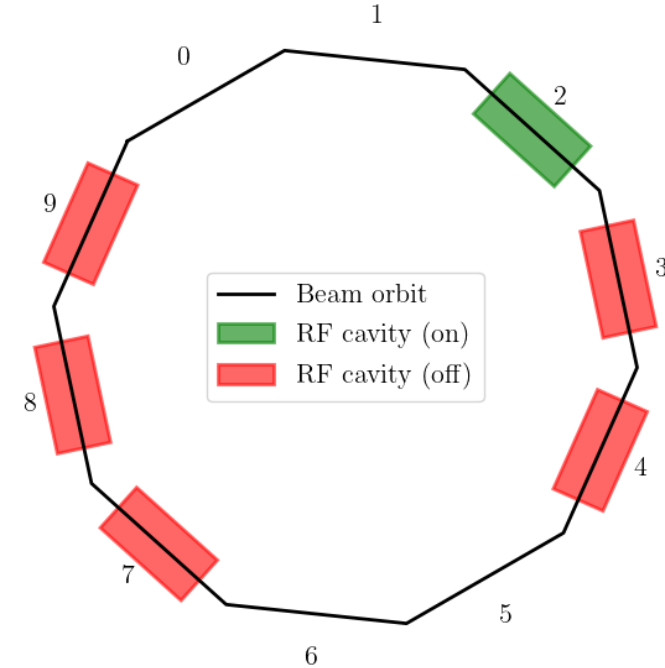
This scenario is equivalent to the situation at the KURNS FFA beam stacking.

No mitigation case



Beam loss when the RF knockout conditions are met.

ISIS fundamental RF cavity layout

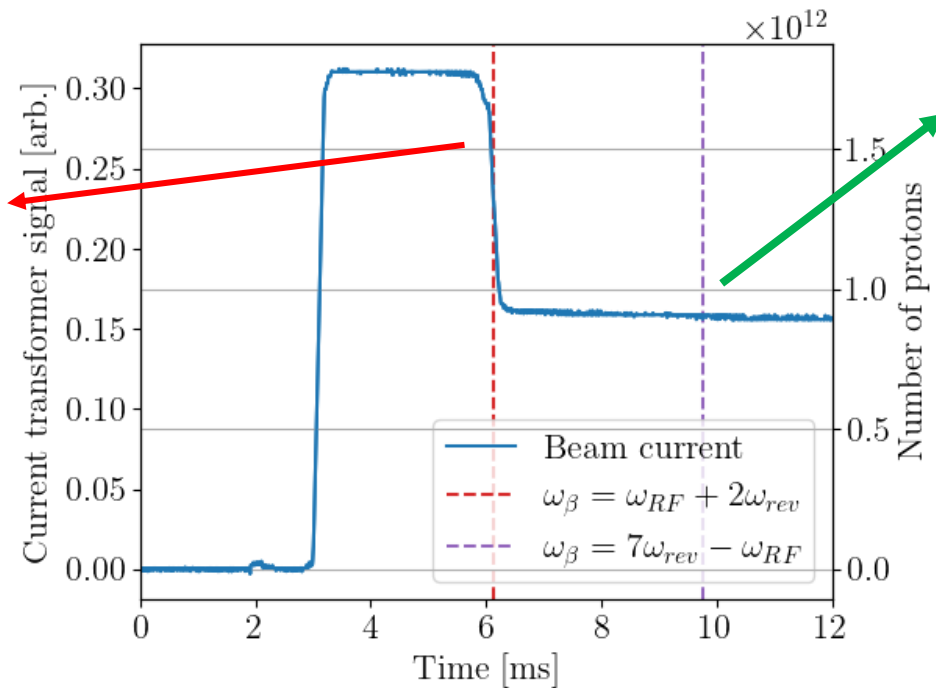


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2 opposite cavities (global cancellation)

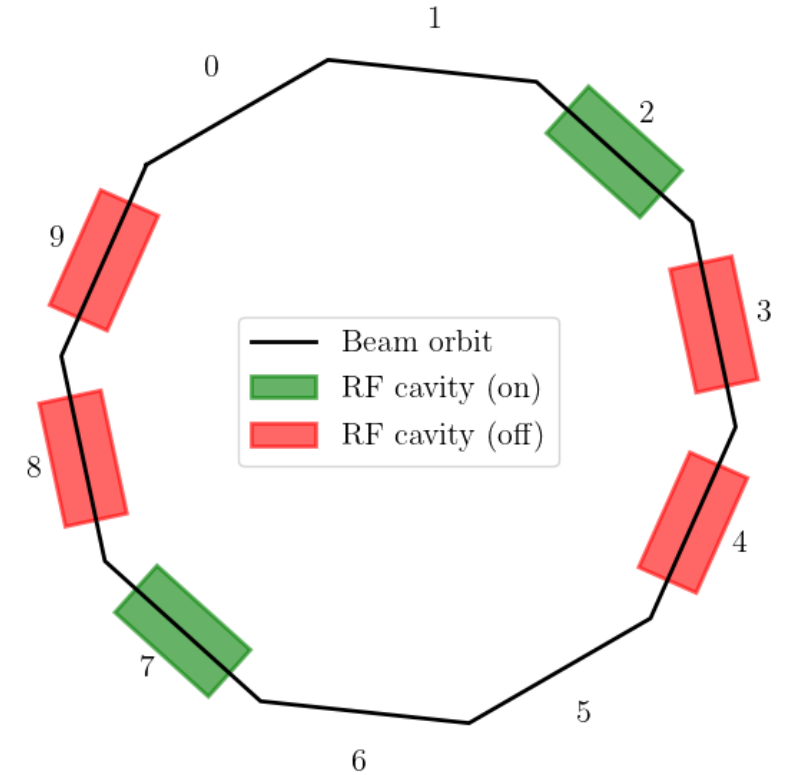
2 RF cavities on exact opposite sides of the ring

This RFKO condition is not cancelled.



This one is cancelled

ISIS fundamental RF cavity layout



By using more cavities, more conditions will be cancelled.

Summary


- FFAs are one option for the proton driver for ISIS-II.
- Beam stacking allows an FFA to accumulate beam and deliver more beam power to the target.
- RF knockout can cause beam loss during the beam stacking RF programme.
- Through a series of experiments at ISIS we've shown it is possible to mitigate the loss from RF knockout.
 - Results published [here](#) and submitted to PRAB.

Back ups



ISIS Neutron and Muon Source


 www.isis.stfc.ac.uk

 [@isisneutronmuon](https://www.instagram.com/isisneutronmuon)

 uk.linkedin.com/showcase/isis-neutron-and-muon-source

Experimental confirmation of RF knockout at ISIS

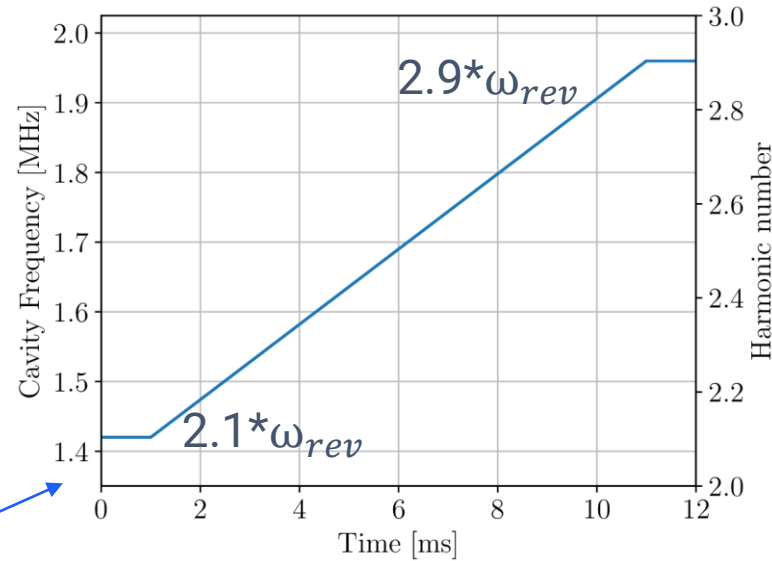
Procedure:

1. Set the magnets to a constant field (ie no acceleration).
2. Inject 70 MeV **coasting** beam. 
3. Run this RF program to **imitate** a Beam Stacking RF program.

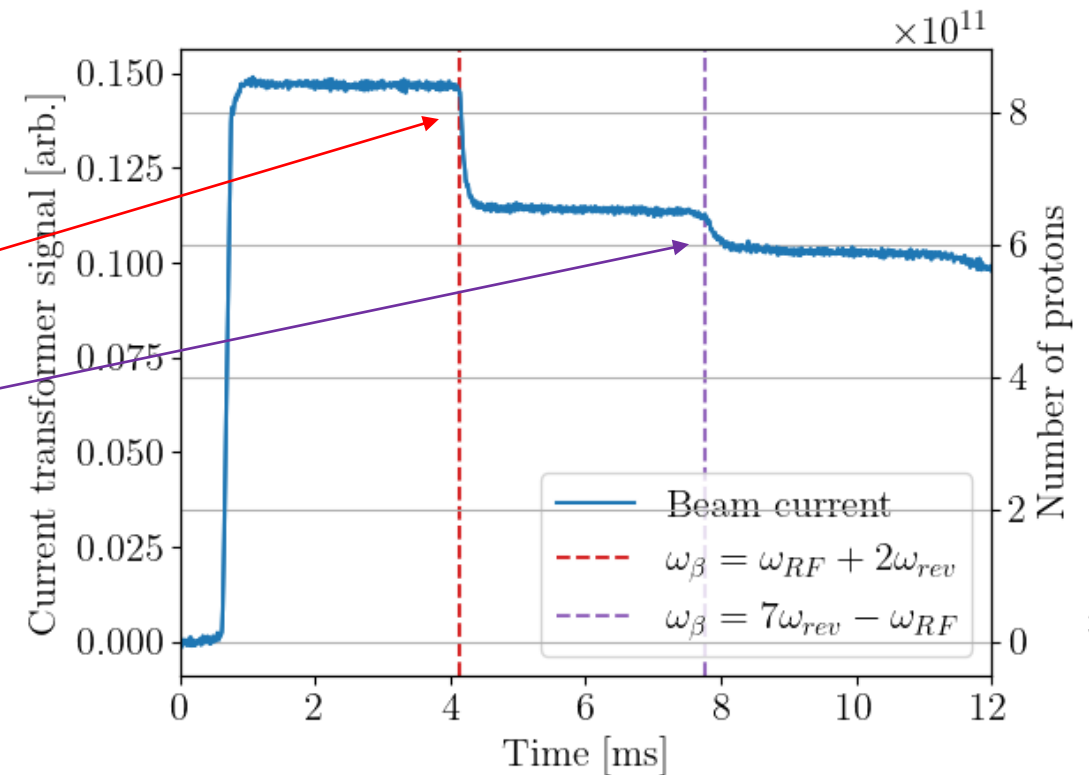
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Beam loss when the RF knockout conditions are met.



Global cancellation

- Using the symmetry of the lattice, it is possible to cancel some of the RF knockout resonances...

$$F(t) = A \sum_{n=-\infty}^{\infty} \left(e^{i(\omega_{RF} + n\omega_{rev})t} \right)$$

Driving force from
one cavity only.



Add term for
 k cavities



$$\sum_k e^{i2\pi(h+n)L_k/C}$$

$L_k = k^{th}$ cavity position in the ring.

C = ring circumference

i.e L_k/C = angular cavity position.

h = harmonic number

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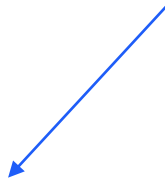
i.e $L_k/C =$ angular cavity position.

$h =$ harmonic number

For two cavities on opposite side of the ring: $\frac{L_k}{C} = \frac{1}{2} \Rightarrow 1 + e^{i2\pi \frac{1}{2} (h+n)}$

Global cancellation with two opposite cavities

- Then the total force becomes:

$$F(t) = Ae^{i(\omega_{RF} + n\omega_{rev})t} \left(1 + e^{-i\pi(h+n)} \right)$$


When $h + n$ is an odd number the RF knockout driving force is zero.

Global cancellation results

- As the two voltage from the two cavities becomes more unequal, the RF knockout displacements return.
 - Zooming into the mitigated condition.
 - Still a small kick even with equal voltages → probably because of the error in the gap volts.

Global cancellation results

- As the two voltage from the two cavities becomes more unequal, the RF knockout displacements return.
 - Zooming into the mitigated condition.
 - Still a small kick even with equal voltages → probably because of the error in the gap volts.
- Unlike the local cancellation this method does not effect the acceleration of the second beam.
 - → But it does not cancel every condition.

