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High Intensity Proton Studies at RAL

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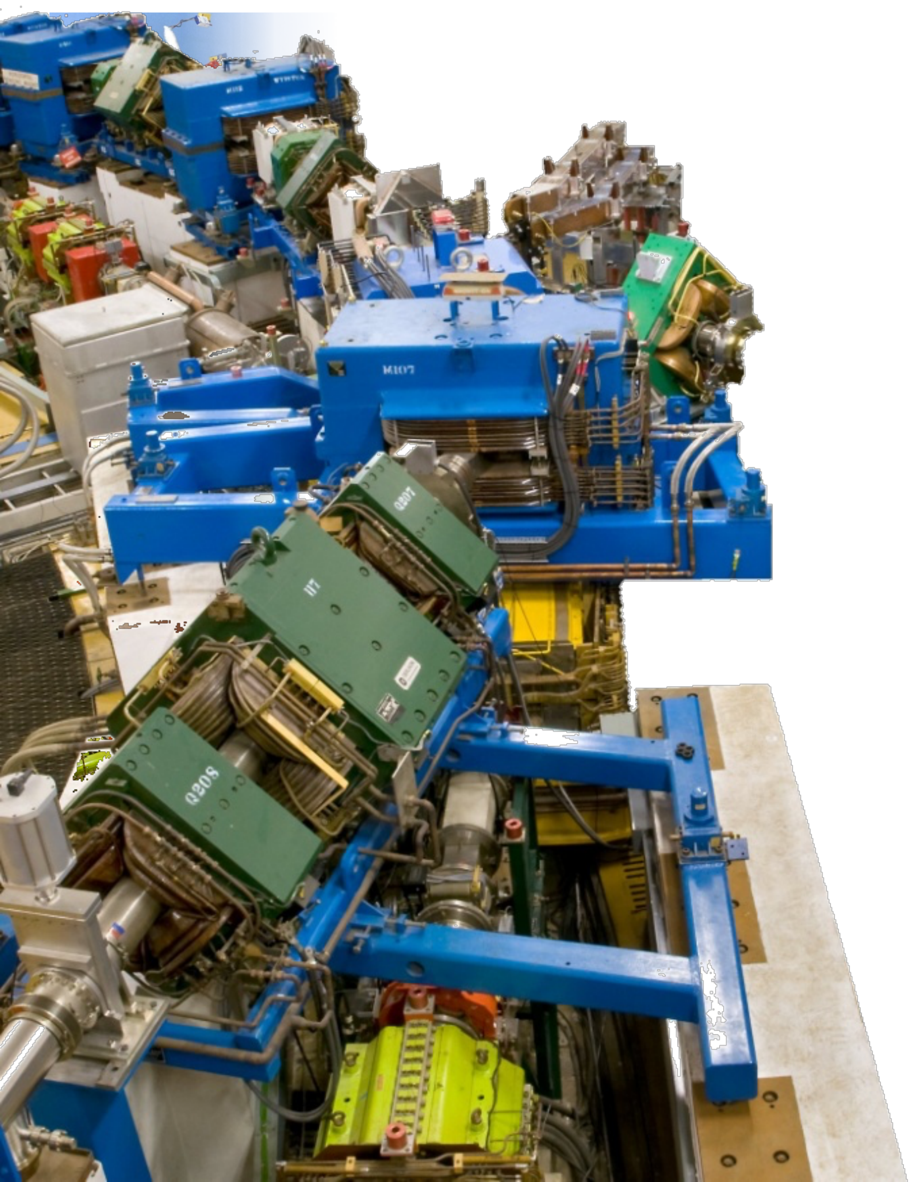
ISIS, Rutherford Appleton Laboratory, U.K.

Background



» Upgrading ISIS to preserve its status as a world leading neutron and muon facility.

» Exploring options for a future multi-megawatt facility on a 20-year time-scale

» Include ideas that could be feasible with advances in technology

» Gain benefit through collaborations with laboratories like CERN and from the developments at future facilities overseas, particularly in China (C-HIAF, C-SNS)

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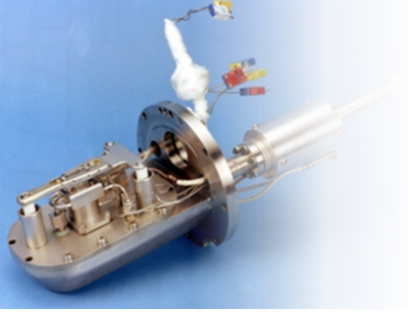
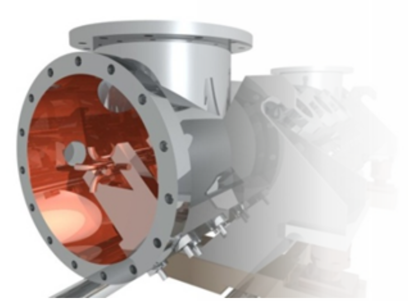
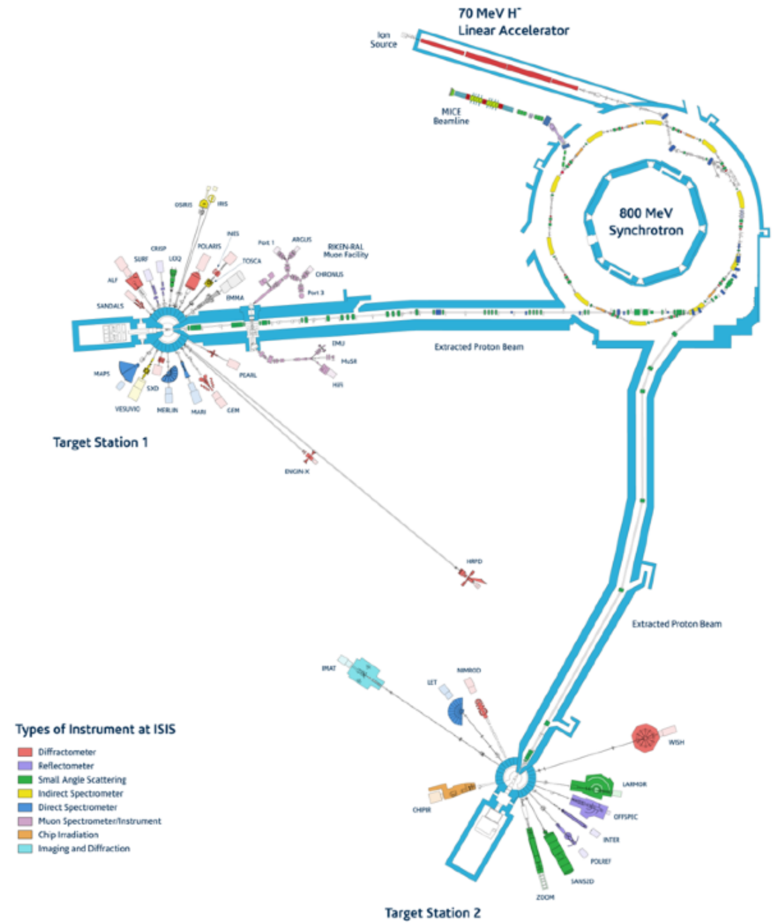
ISIS Accelerators





- » H^- ion source (17 kV)
- » 665 kV H^- RFQ
- » 70 MeV H^- linac
- » 800 MeV proton synchrotron
- » Extracted proton beam lines



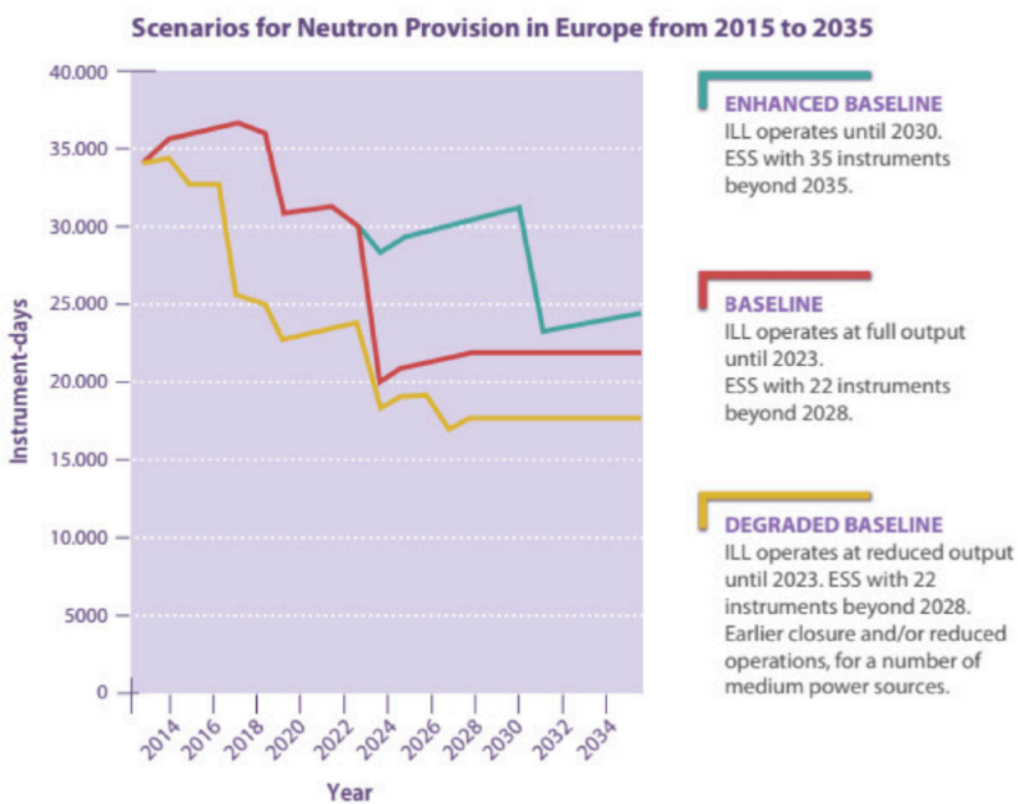
The accelerator produces a pulsed beam of 800 MeV protons at 50 Hz.

Average beam current 220 μA (2.8×10^{13} ppp).

176 kW on target (140 kW to TS-1 at 40 pps, 36 kW to TS-2 at 10 pps)

Neutrons in Europe

- ESFRI ESFRI Physical Sciences and Engineering Strategy Working Group Neutron Landscape Group - Neutron scattering facilities in Europe: Present status and future perspectives:
  - identified a shortage of neutrons in Europe after ILL closes.
- Possible upgrades to ISIS under study for many years, but now is a good time to re-focus given the advent of ESS and the impending ‘neutron drought’ in Europe.
- ISIS-II Working Group has been set up, and consists of experts from accelerator, target, neutronics, instrument science, detector and engineering.
- *Important to stress that this must be envisaged as a facility upgrade, not simply an accelerator upgrade*



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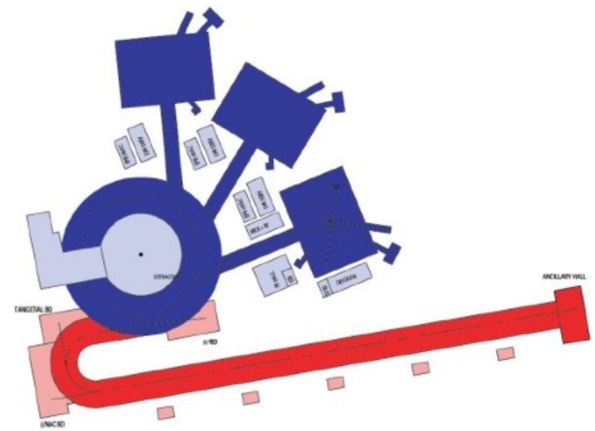
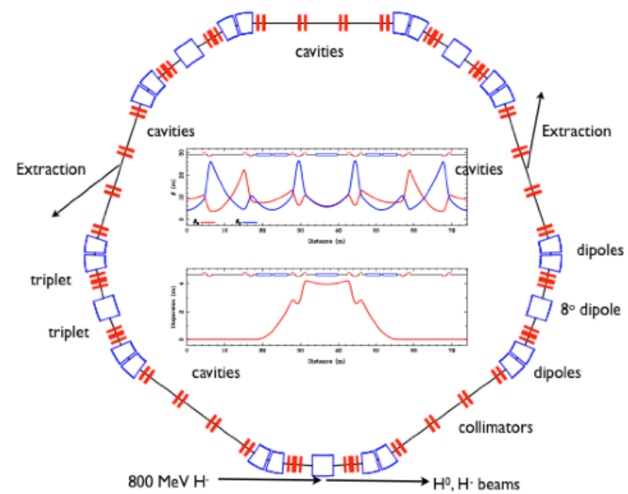
Ideas for ISIS MW-level Upgrades

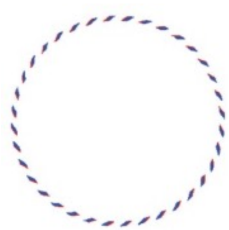
- Provision for multiple optimised targets with different beam powers, repetition rates, according to user requirements
- Options for future upgrades to multi-MW (perhaps using stacked rings)
- Advanced facility for both neutrons and muons
- Concepts:
  - 0.8 GeV superconducting linac + 0.8-3.2 GeV Rapid Cycling Synchrotron
  - Fixed Field alternating gradient Accelerator: lower injection energy, higher efficiency and reliability, operate at high intensity
  - Higher energy linac + accumulator ring
  - A completely new accelerator within existing ISIS infrastructure (provided off-time can be tolerated)
    - Likely to be cheapest possible option
    - Only ISIS-II option that guarantees the facility stays in the UK (and at RAL)



0.8 - 3.2 GeV RCS

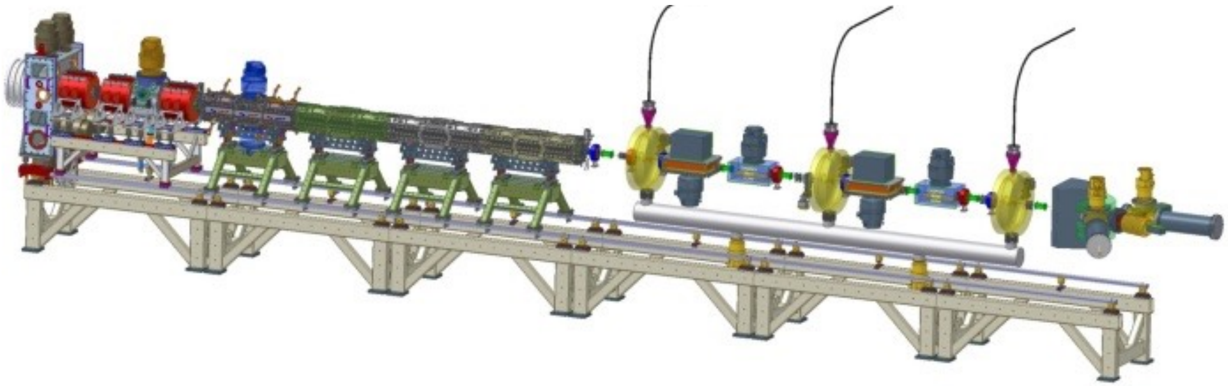


0.4 - 3.2 GeV FFA



Compact Neutron Source

- Recent interest in a compact short pulse option with proton energy in the range 14 – 20 MeV
- Could be an extension of the Front End Test Stand at RAL.



- Other alternative uses (e.g. fusion materials irradiation, single event effect testing with protons) could be considered.

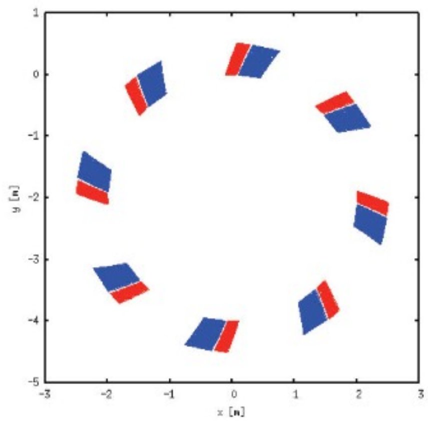
Compact Neutron Source

» Studying FFA alternatives to take output from FETS (3 MeV) directly to required energy and pulse structure

– Study high intensity beam dynamics to establish whether FFAs are really a possibility for ISIS-II

– Prototype relevant components

– Ties in with IBEX Paul trap experiment set up at RAL (talk by **Suzie Sheehy on Wednesday morning**)



Type	DF-Spiral
Kinetic energy	3 - 27 MeV
Pex/Pin	3
Cell number	8
Packing f	0.31
Spiral angle	20
Field index	3
Orbit excursion	0.48 m
Rex/Rin	2.1 / 2.6 m
Bmax@orbit	1.7 (1.9) T
Straight	1.1 m

» Lower risk (but less interesting) alternative is warm DTL to required energy, followed by an accumulator ring.

» Should be used to allow us to demonstrate technology readiness in areas we are not covering under another banner (ISIS sustainability, other UK proton R&D).

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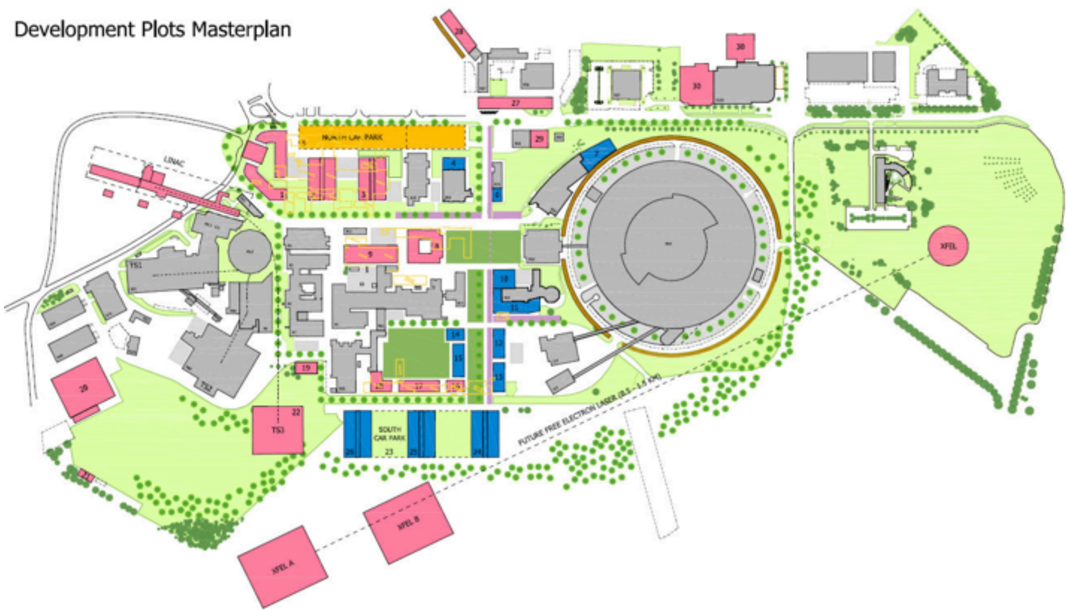
ISIS-II

- Focussed on ~1 MW short pulse neutron and muon facility using existing ISIS tunnel (R~25 m).
- Beam should supply one or more targets.
- Studies cover a new accumulator ring (AR), a rapid cycling synchrotron (RCS) and novel fixed field rings (FFA).
- Prototype test ring planned using existing 3 MeV FETS (Front End Test Stand) as injector.



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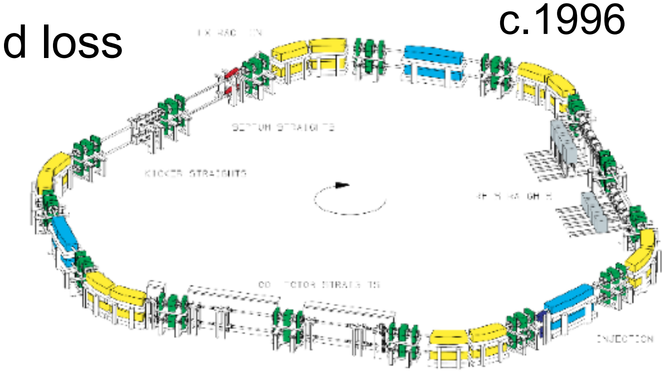
ISIS-II Conventional Accumulator and RCS Options

- Aim to find the optimal configuration for ISIS II
  - Study conventional AR and RCS in detail: Compare with FFA ⇒ pick the best
  - Specification from users: Two targets 10 Hz, 0.25 MW; 40 Hz, 1.0 MW
- Important considerations:
  - Re-use of ISIS infrastructure or stand-alone
  - Conservative design, or are gains possible by pushing established limits
- Presently looking at 1.25 MW options for ISIS Hall, R=26 m
- Have revisited old ESS (1996) design: 1.3 GeV AR, R=26 m
  - Interesting lattice and dispersive injection
  - Some re-working of dynamics and new simulation studies
  - Plausible 1.25 MW: limits on foil temperature and loss
- Now looking at new RCS designs
  - Cheaper linac
  - Key challenges: foil temperatures, losses

ESS rings
c.1996

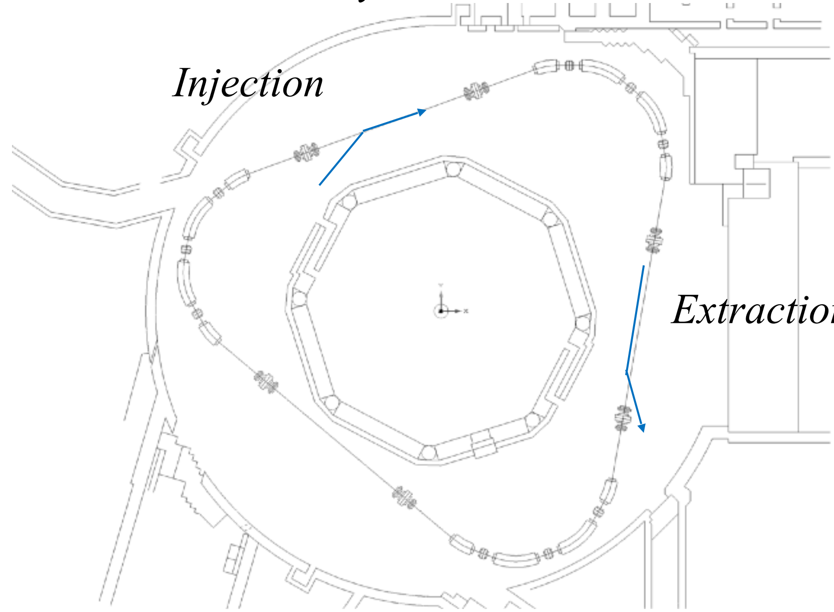


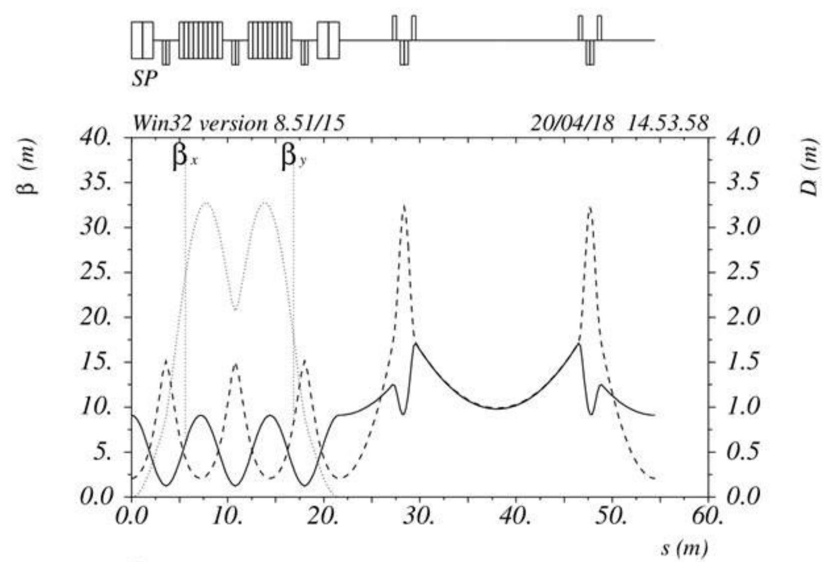
ISIS-II: Present RCS Design under Study

Outline Specification*

Energy Range	0.4 – 1.2 GeV
Intensity	1.3×10^{14} ppp
Repetition Rate	50 Hz
Mean Power	1.25 MW
Circumference (mean R)	163 m (26 m)
No. Super-periods	3
Nominal Tunes	(Q_x, Q_y)=(4.40, 4.36)
Magnet Excitation	Sinusoidal
Dipole Fields	0.49 – 0.99 T
Gamma Transition	3.78
Peak RF h = (2, 4)	(240, 120) kV/turn
RF Frequency (h = 2)	2.62 – 3.30 MHz
Number of Bunches	2

Layout in ISIS Hall





- 3 SP ring fits within ISIS hall and is aligned to accommodate existing injection and extraction paths.
- Lattice has long achromatic straights for H^- injection, extraction, RF and collimation

*See IPAC18, D J Adams et al., TUPAL058

Beam Studies and Intensity Limits

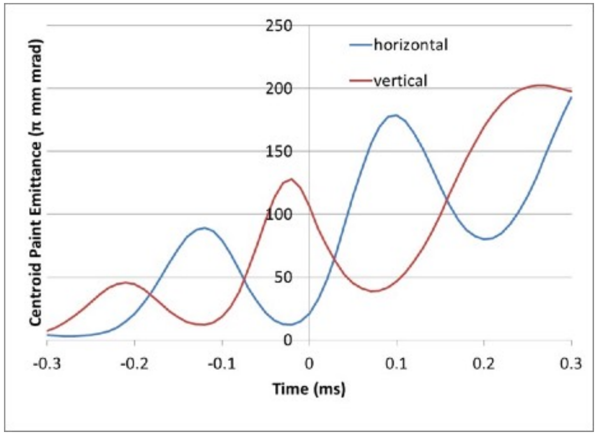
Performance of RCS at 1.25 MW

- » Numerically optimised injection painting
  - – Reduces foil hits to ~2.3
  - – Carbon foil temperatures ~1800 K
- » 3D ORBIT simulations, losses in 0.02% regime
  - – Error study underway
- » Much optimisation and study to do
  - – Injection process (emittance evolution)
  - – Space charge, working point
  - – Instabilities, collimation, extraction

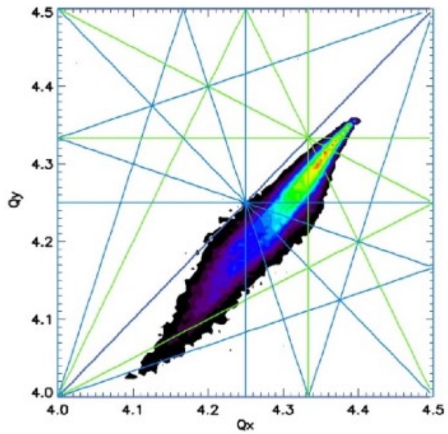
Comparative assessment of other rings

- » Will repeat study for
  - – Lattice variations, AR, standalone
  - – Topics that overlap with FFA work
- » Limiting factors, interesting ideas
  - – Run with higher space charge: predict loss?
  - – Larger apertures, direct proton injection
  - – Two stacked rings make 2.5 MW possible

Centroid painting vs time



Tune footprint after injection



Simulations with ORBIT

Fixed Field Accelerators (FFA)

- FFAs may be a good choice for a high intensity machine in view of their flexibility
  - no ramping, stable dc power supplies
  - high repetition rate (100 Hz and up), restricted only by rf programme
    - increased beam power
    - ability to match users' requirements
  - horizontal beam extraction easier
- Large momentum acceptance; particles with injection and extraction energy can circulate at the same time;
  - beam stacking
  - horizontal emittance can be enlarged
- Superconducting or permanent magnets can be used
  - high energy efficiency, high availability, low operational costs

Studies have covered several types of FFAs (scaling, non-scaling, pumplet) but are now focussing on the DF-spiral. (Machida, Phys.Rev.Lett. 119, Aug 2017). A 0.4-1.2 GeV main ring and a 3-30 MeV test ring are being considered.

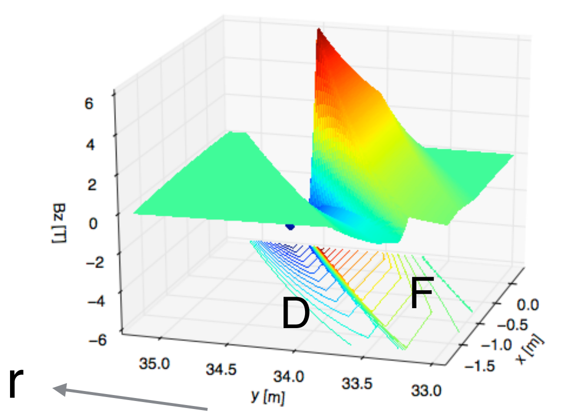
DF-Spiral FFA

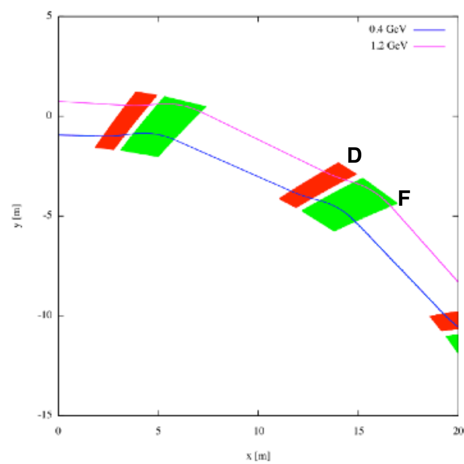
» Combines features of radial and spiral FFAGs to give a compact, versatile design

$$\begin{aligned} Q_h^2 &= k+1 \\ Q_v^2 &= -k + f^2 \tan^2 \zeta \end{aligned} \quad \text{where} \quad \begin{aligned} \zeta &= \text{spiral angle} \\ f &= \text{flutter} \end{aligned}$$

$$B = B_0 \left(\frac{r}{r_0}\right)^k \left\{1 + f \cos\left[N_{\text{cell}}\theta - N_{\text{cell}} \tan\zeta \ln(r/r_0)\right]\right\}$$

» Introduce small negative field on one side of main spiral magnet to generate sharp edge between D and F and increase flutter f.





ISIS-II based on DF-Spiral FFA

Find sets of parameters for both a main ring for the ISIS tunnel and a small prototype test ring to go on FETS

Basic considerations for design:

» Choice of number of cell

» Choice of spiral angle

» Orbit

- Excursion
- Magnetic field along the orbit

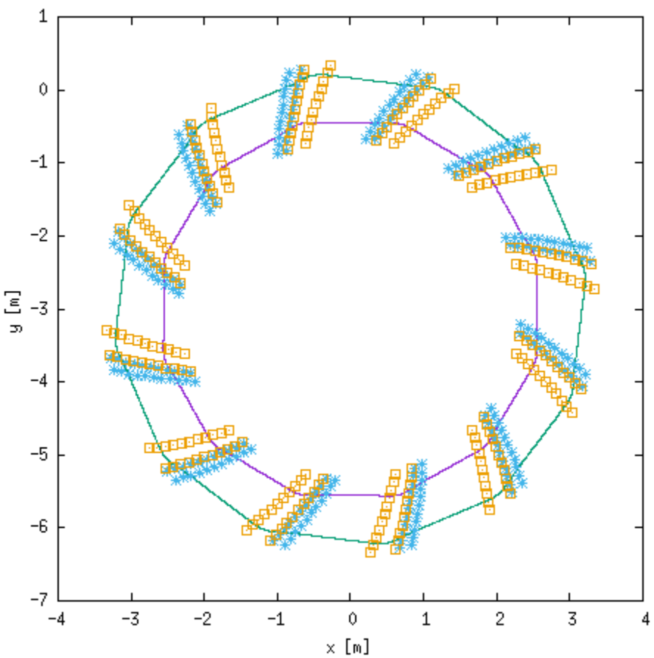
» Optics

- Courant-Snyder parameters
- Range of parameters for injection study

» Tuning adjustment

» Acceptance and space charge effects

» RF parameters



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ISIS-II and Test Ring Parameters

Parameter	**ISIS-II**	**Test Ring**
Kinetic energy	0.4-1.2 GeV	3-30 MeV
Mean radius at injection	24 m	4 m
Number of cells	25	15
Magnet length (D,F)	(0.60 m, 1.21 m)	(0.17 m, 0.34 m)
Packing factor	0.35	0.35
Straight section	3.58 m	1.03 m
Spiral angle	62°	41°
k index	20.6	7.2
B_d/B_f	-0.47	-0.36
Orbit excursion	0.8 m	0.6 m
Nominal cell tune (H,V)	(0.20760, 0.20960)	(0.21267, 0.21600)
Nominal ring tune (H,V)	(5.19, 5.24)	(3.19, 3.24)
Transition gamma	4.6	2.9

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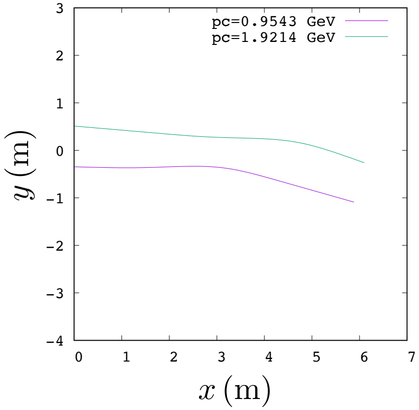
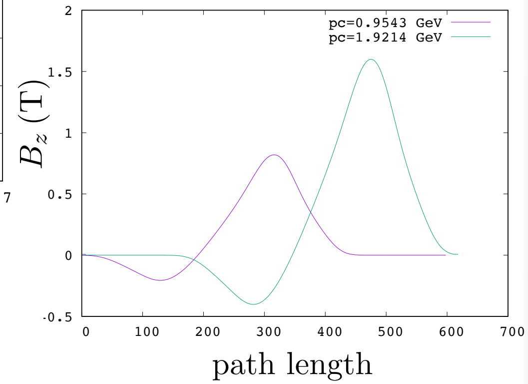
ISIS-II and Test Ring: Orbit and Optics

ISIS-II 25 cell DF-spiral lattice

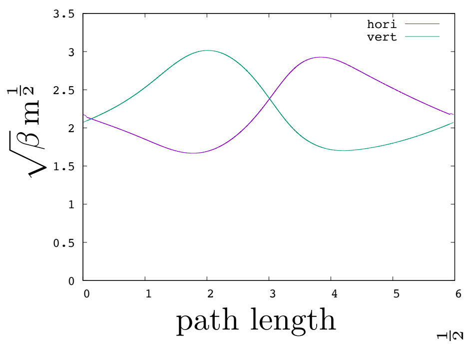
orbits from above



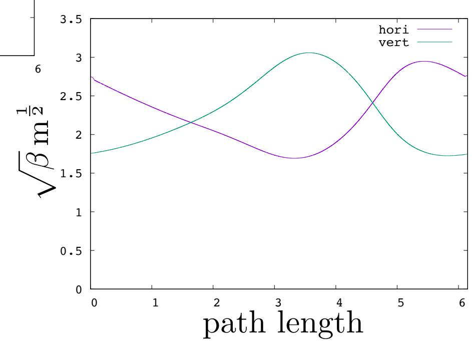
field along orbit



injection optics

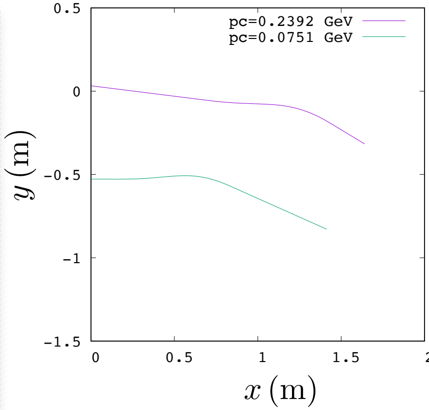


extraction optics

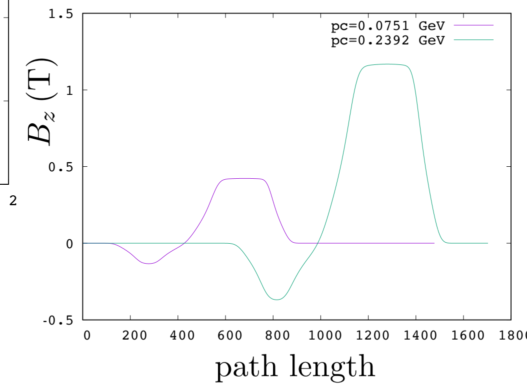


Test ring 15 cell DF-spiral lattice

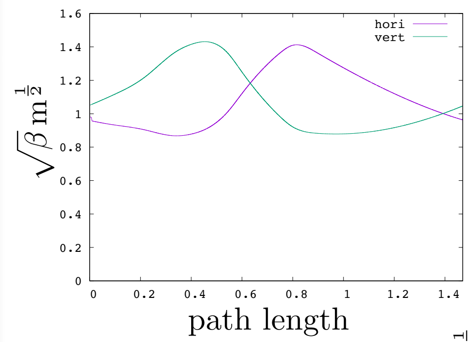
orbits from above



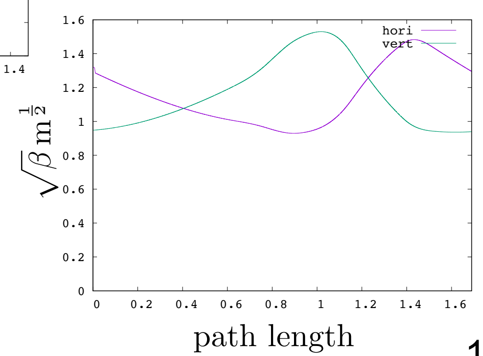
field along orbit



injection optics

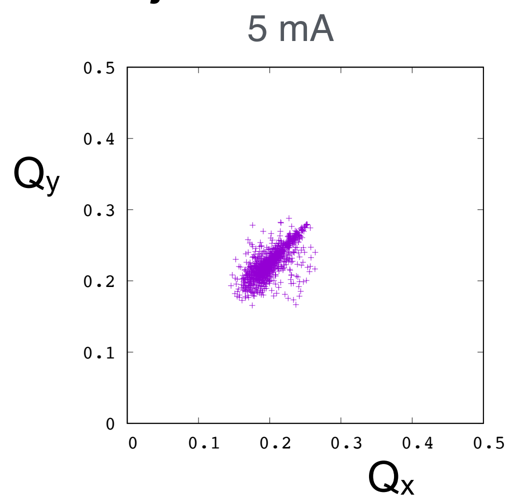


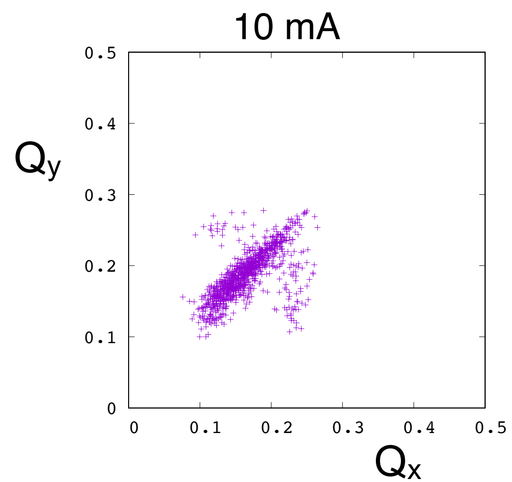
extraction optics



Space Charge Tune Shift

- » Space charge tune shift becomes about **-1.0** when a 50 mA FETS beam is injected for one turn.





- » Can we hold such high space charge beams in a ring?
- » Similar questions were asked at the UMER project at University Maryland (but that is an electron ring).
- » We could use the (pulse compressed) beams for some applications.

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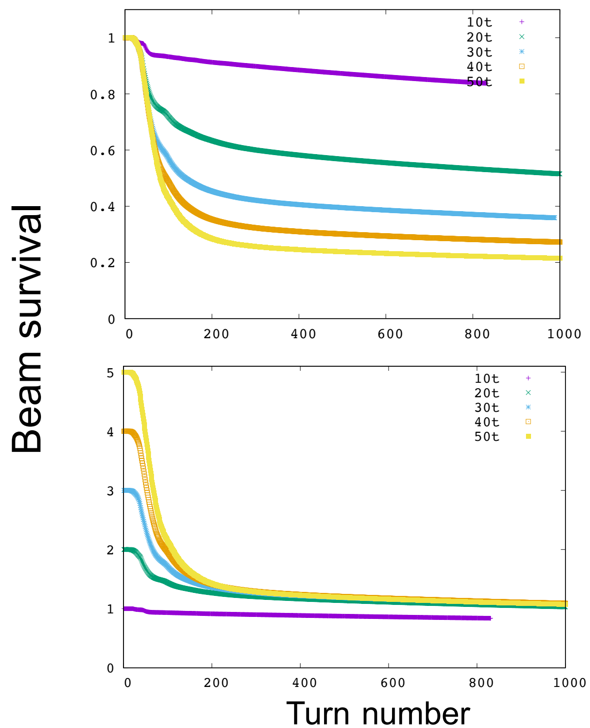
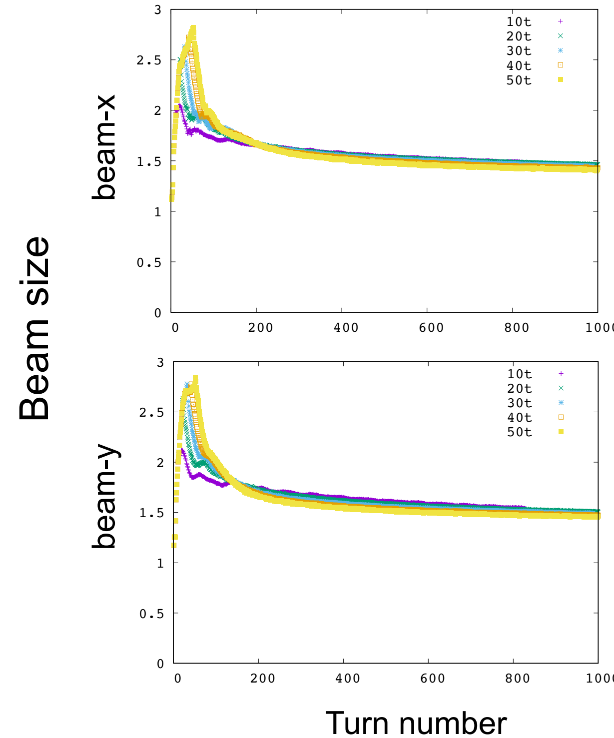
Intensity Limit

- Inject 10, 20, 30, 40, 50 turns of 50 mA linac beam and look at beam size and fraction surviving.
- An rf voltage is applied and the beam is captured in a bucket.





- 20 turn accumulation (1 A) seems a hard limit. How do we interpret this?
  - 50 mA causes tune shift of -1.0.
- Beams end up with similar distributions

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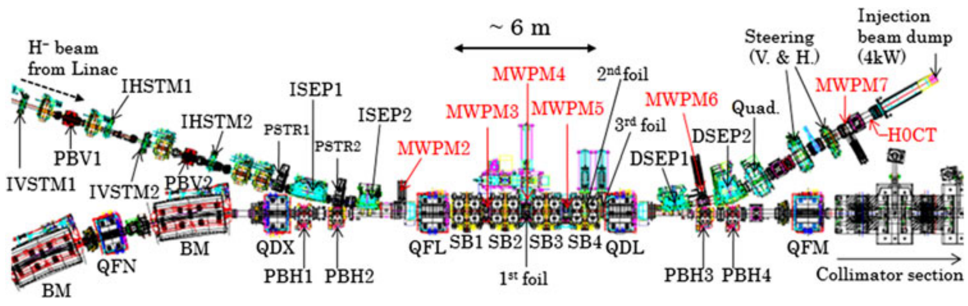
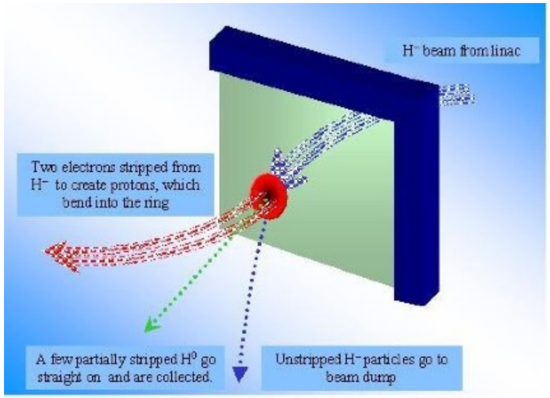
Proton Beam Accumulation

» Traditionally achieved via H^- charge exchange injection (non-Liouvillean)

- » Complicated injection chicane
- » Needs a mechanism for handling unstripped H^-, partially stripped H^0 excited states and removal of stripped electrons
- » Foil traversals leading to heating and lifetime issues, nuclear scattering, multiple scattering, foil replacement system
- » Intra-beam stripping in linac and injection line
- » These all contribute to beam loss.

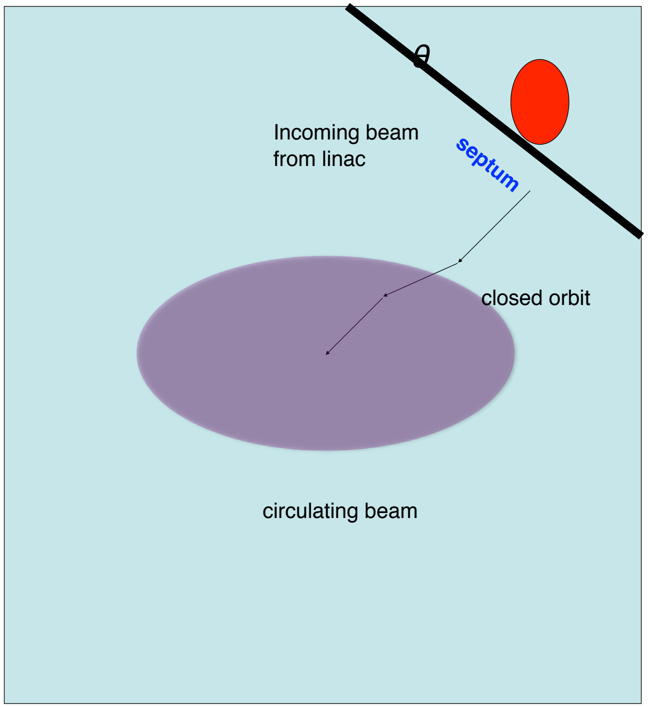




» Direct proton injection (Liouvillean) is a possible alternative

Direct Multiturn Injection of Protons

- Liouvillean injection using a tilted electrostatic septum.
- Injection simultaneously into 4D transverse phase space
- Optimise h and v closed orbit bumps to minimise beam loss
  - equivalent to minimising foil traversals in an H^- system
- Simple injection chicane.
- Challenges the idea that the accumulation of a high intensity, pulsed, proton beam can only be achieved via charge exchange injection of H^-.
- Relies on developments in technology over the past 20 years.
- Builds on techniques used for optimising H^- injection systems developed for ESS/SNS/J-PARC/CSNS etc.
- Adopted at C-HIAF and under study as a possible option for a neutrino superbeam facility at ESS (ESSnuSB)
- Note that higher currents are available for a proton linac *cf* H^-.



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Injection

- Requires careful choice of septum angle θ and ring optics (tunes, β-functions at injection point).
- MISxxx codes developed to provide initial parameters of the system (zero space-charge). (See talk WEAM6X01 at HB2016)
- Multiple studies suggest that a reliable ‘Figure of Merit’ is

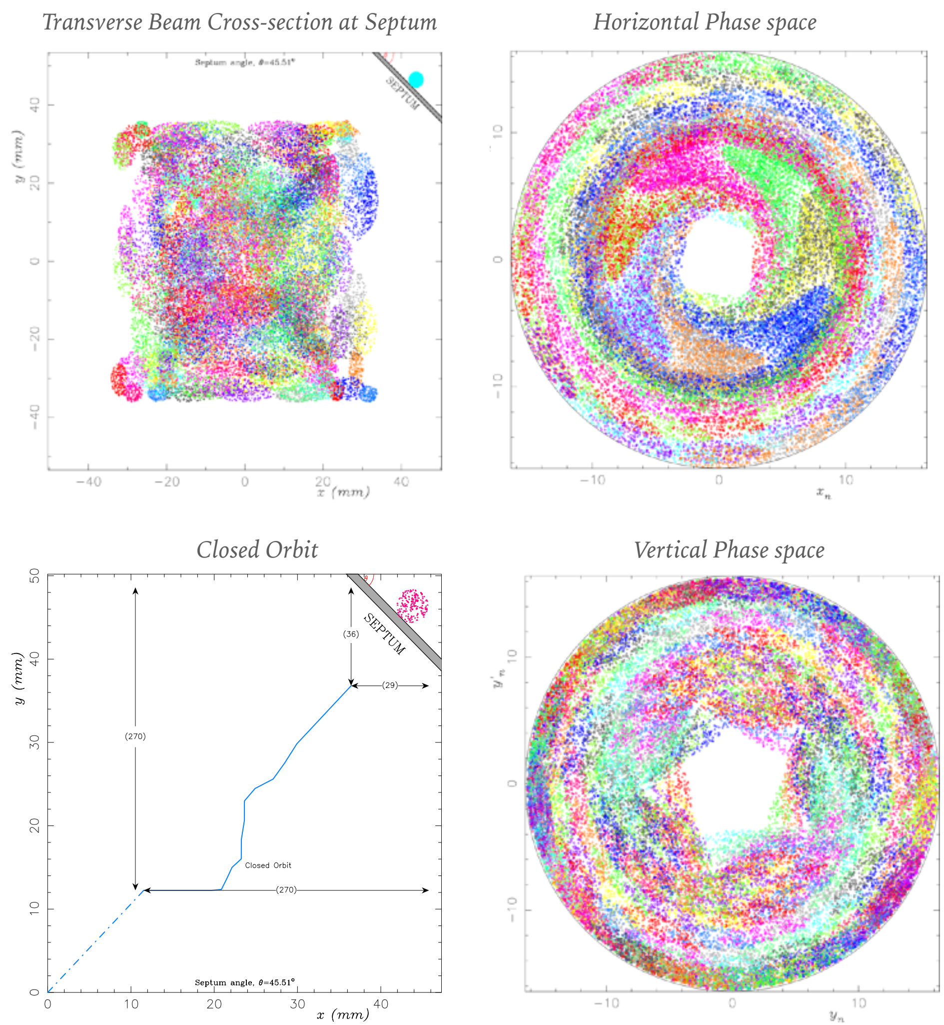
$$\mathcal{F} = \frac{(\epsilon_x \epsilon_y)_{\rm Ring}}{N_{\rm turns}(\epsilon_x \epsilon_y)_{\rm injected}} \approx 10$$

- Directs design:

$$\frac{Ne\beta c}{2\pi R} = \chi I_l N_{\rm turns}$$

$$\Longrightarrow \quad \chi I_l = N \left(\frac{\epsilon_i}{\epsilon_R}\right)^2 \mathcal{F}\, \frac{e\beta c}{2\pi R} \lesssim 200\,\text{mA}.$$

chopped linac current	$\longleftrightarrow$	emittance ratio for total of N particles in ring

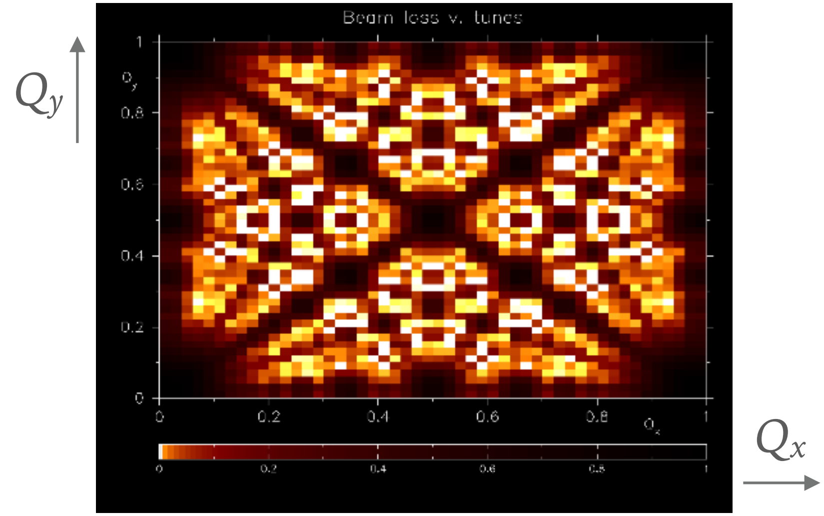


250 turns proton injection for ISIS-II, zero space-charge model

Injection Optimisation

» Important parameters are angle of septum, closed orbit bumps and ring tunes.

White areas represent combinations of tunes for which a tilt angle and orbit bumps can be found for a painting scheme with zero beam loss. Black areas correspond to full beam loss



» Designs from the MIS-codes (Multiturn Injection Schemes): MISHIF, MISOPT, MISPLOT

Optimum conditions for packing turns together

$$\frac{\alpha_i}{\beta_i} = \frac{\alpha_m}{\beta_m} = -\frac{x_i' - x_o'}{x_i - x_o}$$

$$\frac{\beta_i}{\beta_m} \geq \left(\frac{\epsilon_i}{\epsilon_m}\right)^{\frac{1}{3}}.$$

m = machine (ring)

i = injection turn

o = closed orbit

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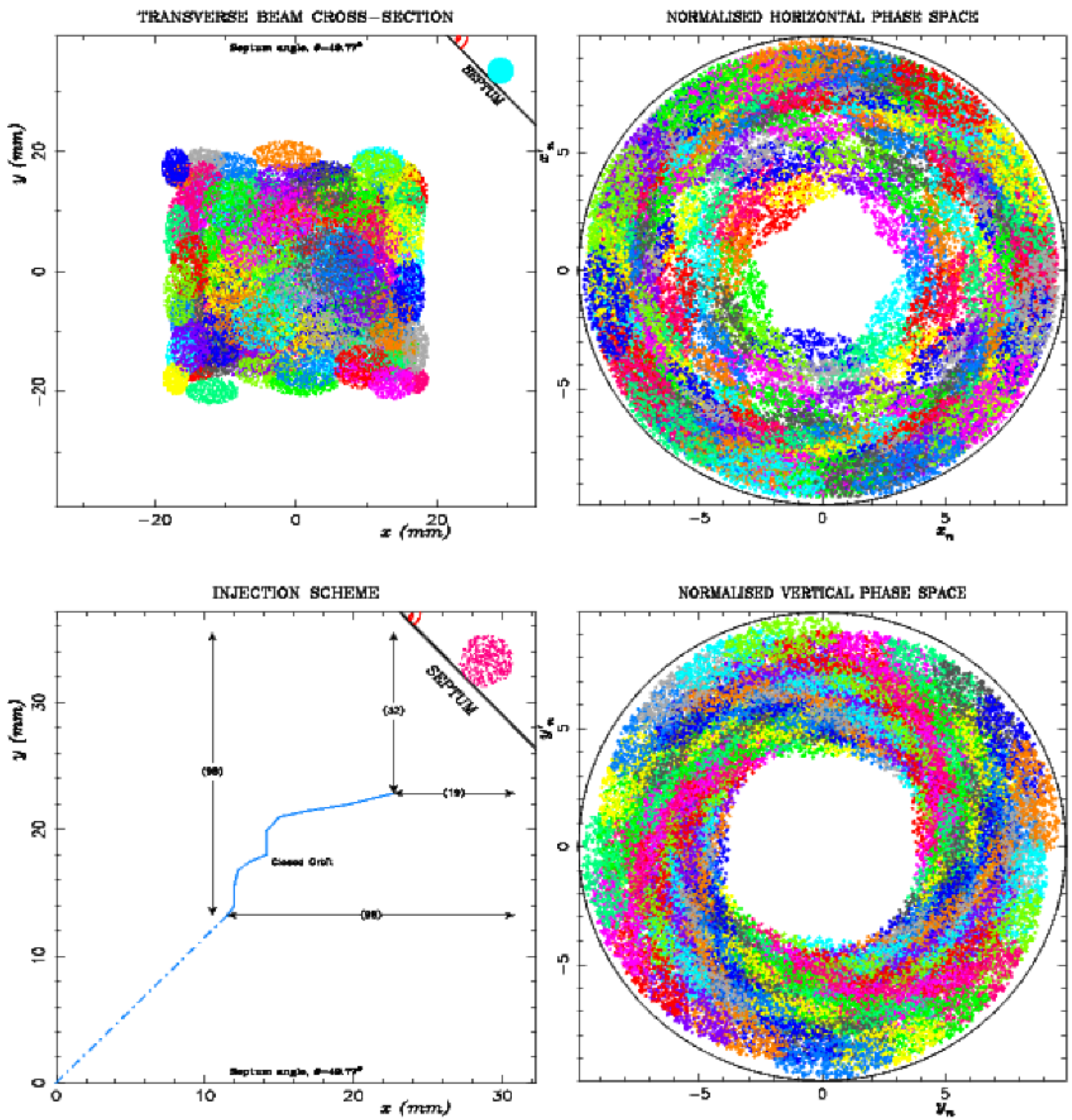
150 Turn Injection into DF-Spiral Main ring

- For $N = 13.2 \times 10^{13}$, $\epsilon_{\text{ring}} = 100\,\pi$ mm.mrad, deduce $\epsilon_{\text{i}} \lesssim 2.7\,\pi$ mm.mrad and 150 injection turns
- Likely linac emittance of $5\,\pi$ mm.mrad must therefore be collimated

Plots show output from the geometrical injection optimisation code MISHIF for 150-turn lossless injection into a DF-spiral ring at 400 MeV using a tilted electrostatic septum. In the model, a maximum chopped linac current of 200 mA is assumed and a septum of 0.1 mm thickness. Tunes are $(Q_x, Q_y) \sim (5.19, 5.24)$. Without collimating the linac beam, the loss rises to over 20%.

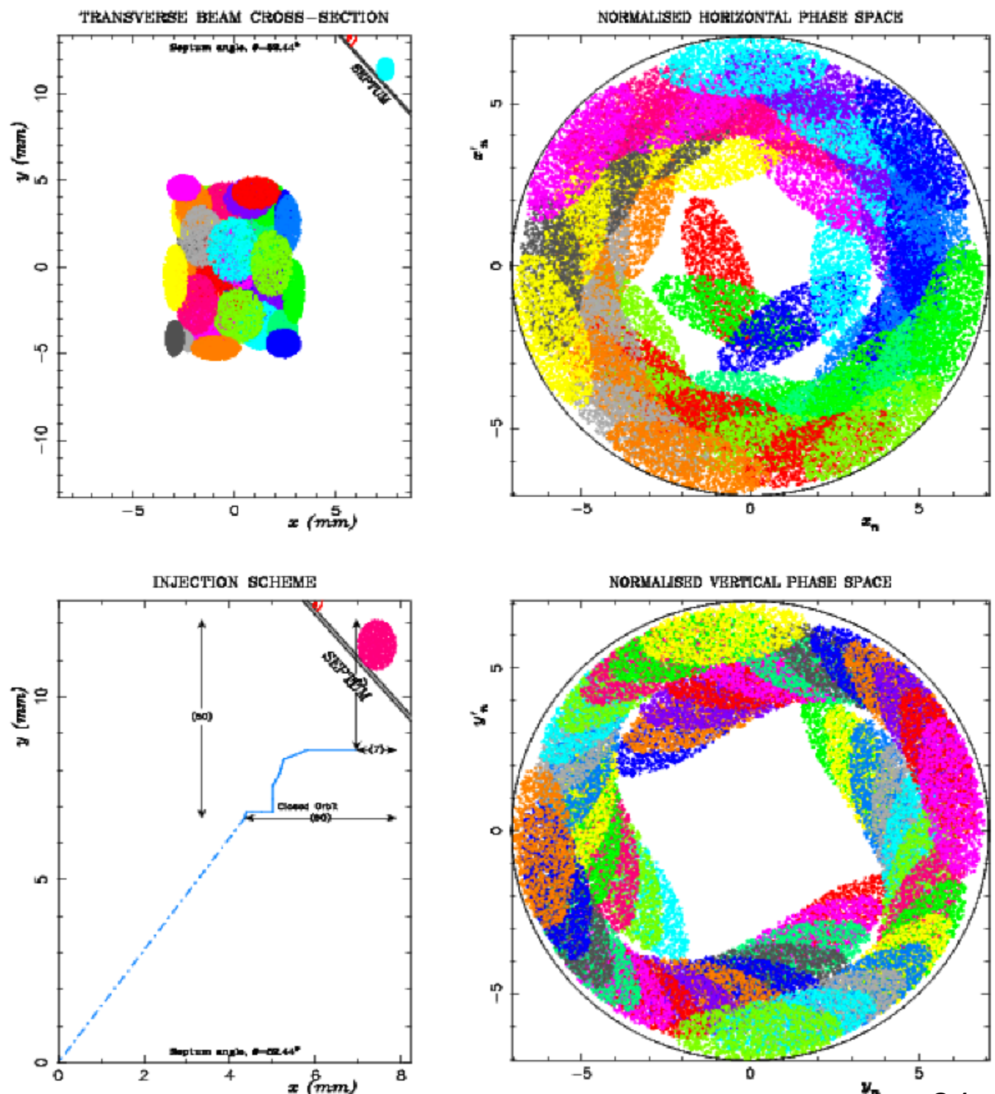


50 Turn Injection into DF-Spiral Test Ring

Similarly for the scaled-down DF-spiral test ring with the same tune depression, 50-turn lossless injection at 3 MeV requires

$$\frac{\epsilon_{\mathrm{ring}}}{\epsilon_{\mathrm{i}}} \gtrsim 22$$

A chopped linac current of 0.54 mA with normalised (100%) emittance $0.18\,\pi$ mm.mrad can be used to paint a ring emittance of $4\,\pi$ mm.mrad.
The tunes are optimised to $(5.15, 5.24)$.



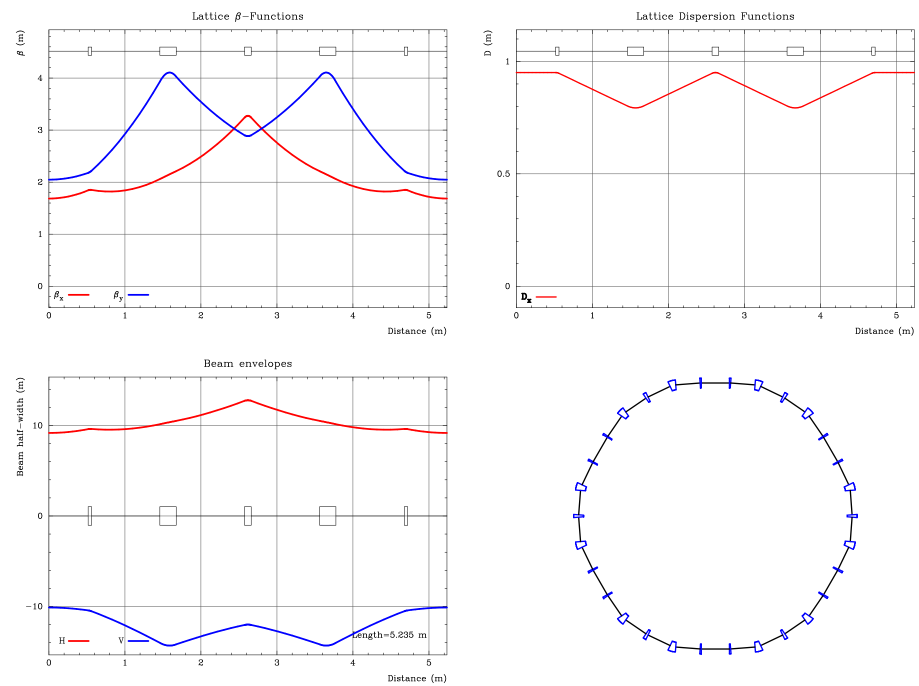
Summary and Comparison

Parameter	Main Ring		Test Ring
	50 Hz	100 Hz	100 Hz
Kinetic energy at injection (MeV)	400.0		3.0
Final kinetic energy (MeV)	1200		30.0
β	0.713		0.0798
$\beta\gamma$	1.017		0.080
100% normalised, painted emittances (π mm.mrad)	100		4
100% unnormalised, painted emittances (π mm.mrad)	98.32		49.98
100%, normalised, linac emittances (π mm.mrad)	2.5	4.0	0.18
100% unnormalised, linac emittances (π mm.mrad)	2.46	3.93	2.25
Chopped linac beam current (mA)	200.00		0.56
Number of ions N	13.2×10^{13}	5.7×10^{13}	13.8×10^{10}
Mean radius of ring (m)	24		3
Expected maximum tune depression ($\times B_f$)	0.22	0.1	0.1
Number of injected turns N_{turns}	150	65	50
Mean beam power	1.27 MW	1.1 MW	66 W

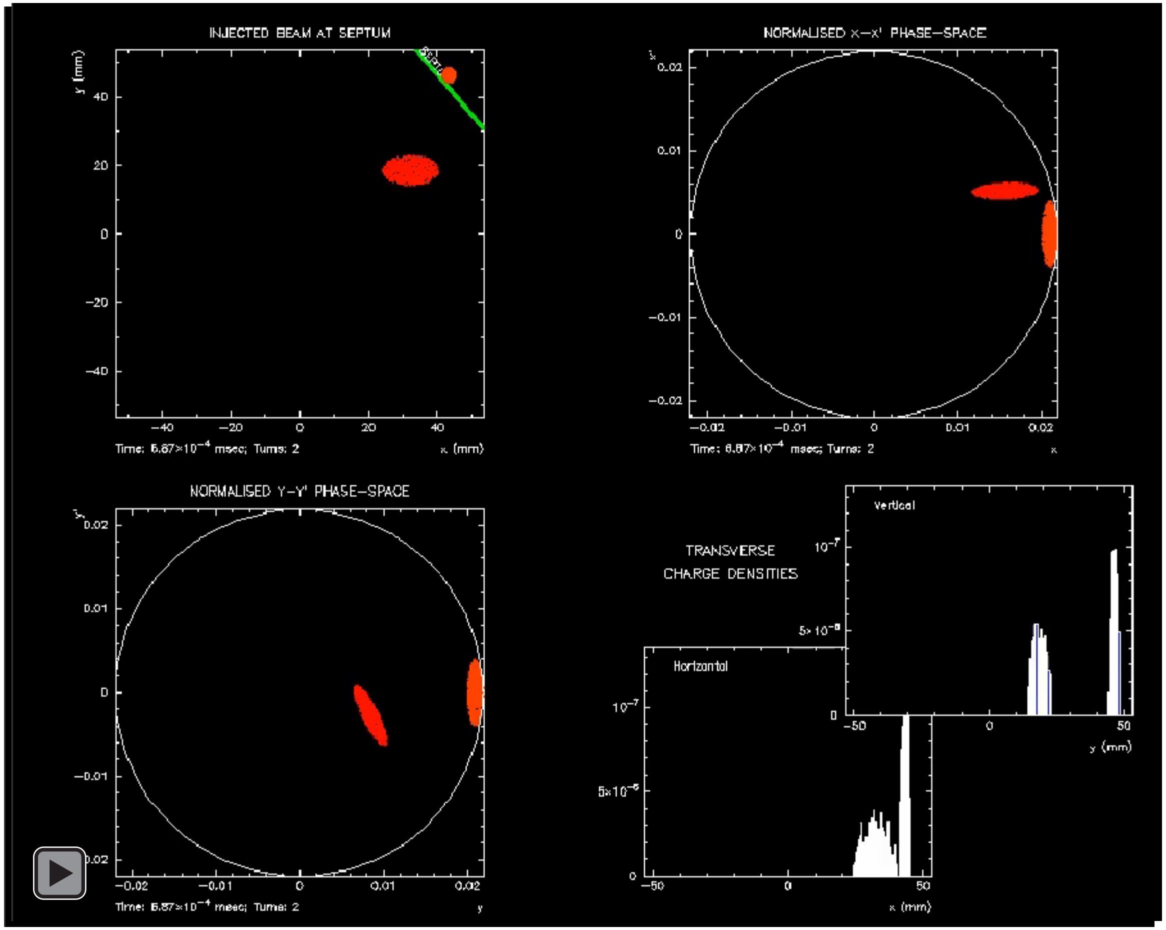
Electron Test Ring (RCS model)

fDfDf Pumplet Lattice, R=5 m

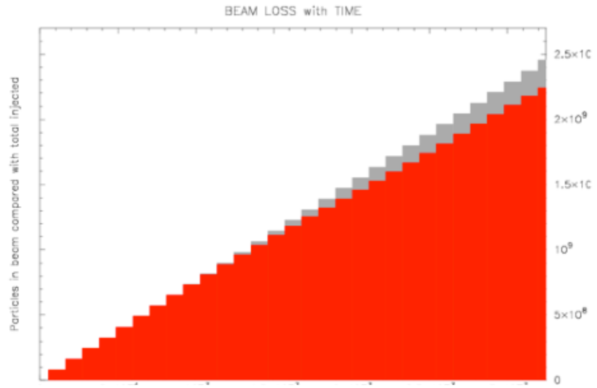
- Electron test ring scaled from main ring RCS study with same tune depression.
- At 1.5 MeV, assume $N_{\mathrm{turns}} \geq 30$ sufficient for validation
- $\epsilon_{\mathrm{ring}} \approx \epsilon_{\mathrm{i}}\sqrt{\mathcal{F} N_{\mathrm{turns}}} \gtrsim 17\epsilon_{\mathrm{i}}$
- For $\epsilon_{\mathrm{i}} \sim 2.5\,\pi\,\mathrm{mm.mrad}$, $\epsilon_{\mathrm{ring}} \gtrsim 11.4\,\pi\,\mathrm{mm.mrad}$.
- For same tune depression as main ring, deduce $\chi I_l \approx 3.5\,\mathrm{mA}$ so $N = 7 \times 10^{10}$ electrons can be accumulated.

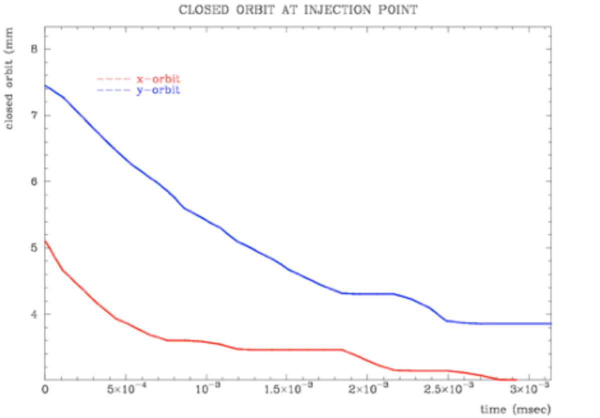


e-RING Injection



Electron ring tracking (incl. space-charge). Unoptimised scenario: 30 turns with nominal tunes Q_h=2.4458, Q_v=1.7449. Predicted lossless without space-charge; loss with space-charge is about 7%.





Summary

» A future new short pulse neutron/muon facility is planned for the U.K. to meet the shortfall in provision after ~2030.

» Options include a new H^- linac and RCS, and a DF-spiral fixed field accelerator with direct proton injection.

» A scaled-down test ring is planned using the existing injector test facility

» We are also working on an accumulator ring for an ESS neutrino superbeam facility (~1500 turns direct proton injection)

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