Upgrades to the ISIS Spallation Neutron Source

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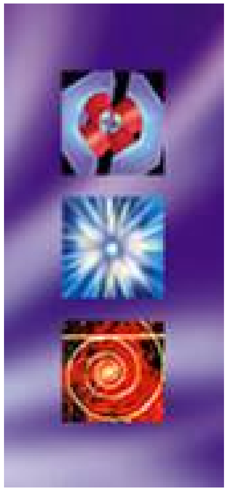
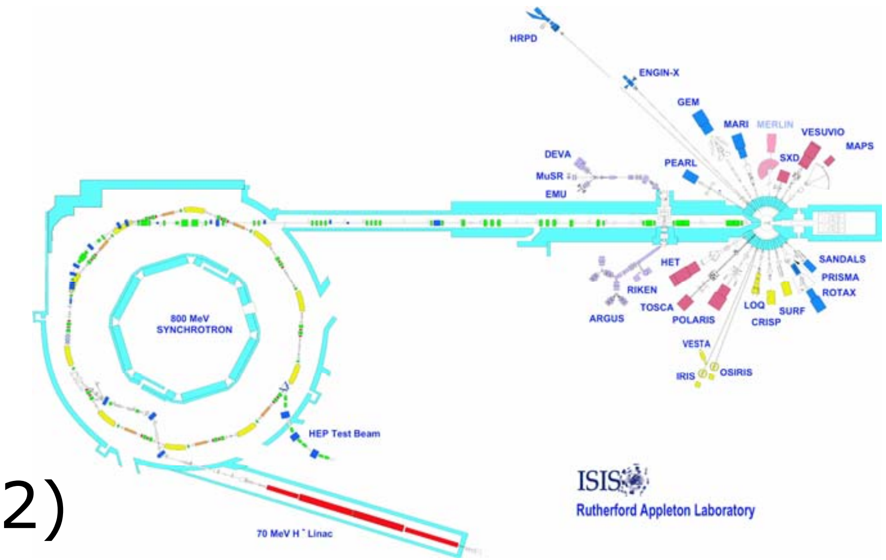


ISIS – the World's Most Powerful Pulsed Neutron Source



2006

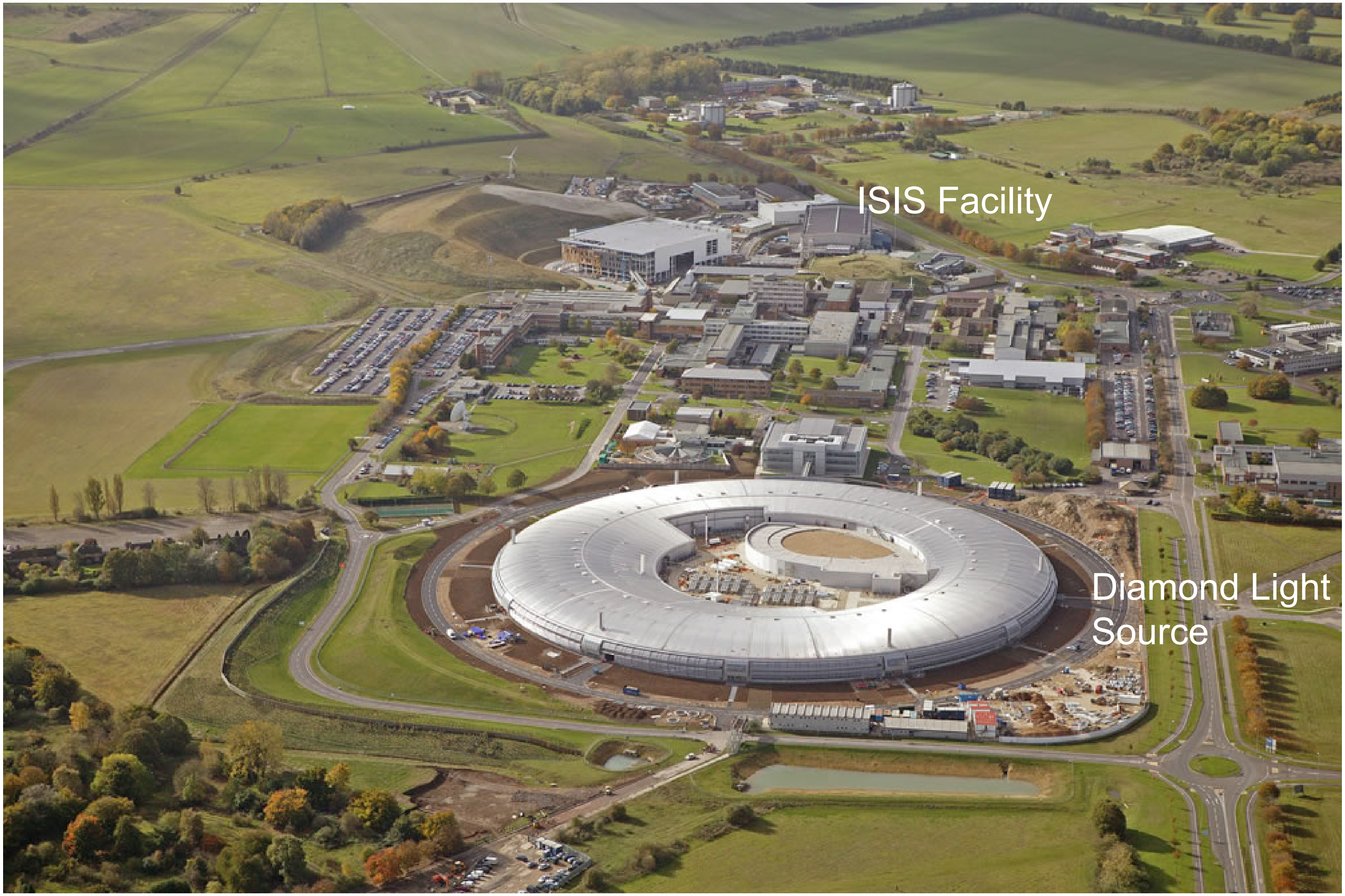
- ISIS today
- 2006 Injector upgrade
- Dual Harmonic RF
- New Target Station (TS2)

2007

- Front-end Test Stand (FETS)
- Linac development (EU/CARE/HIPPI)
- Motivation for a future high intensity proton driver
- Ideas for future ISIS upgrades

ISIS sited at Rutherford Appleton Laboratory, UK

RAL Today



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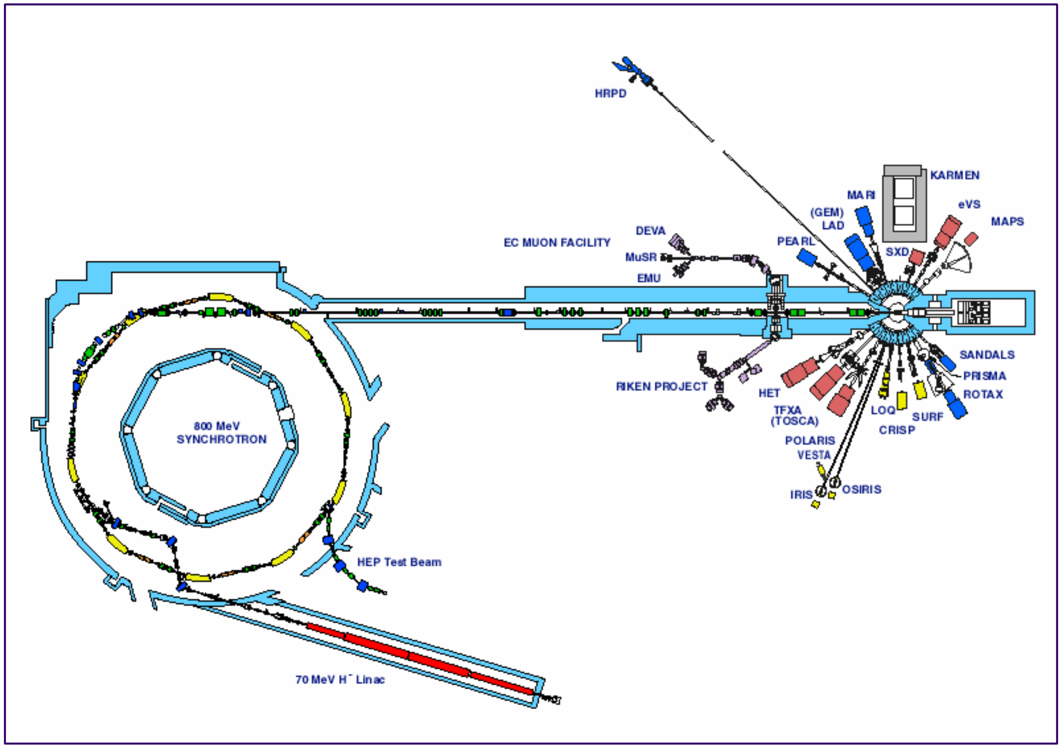
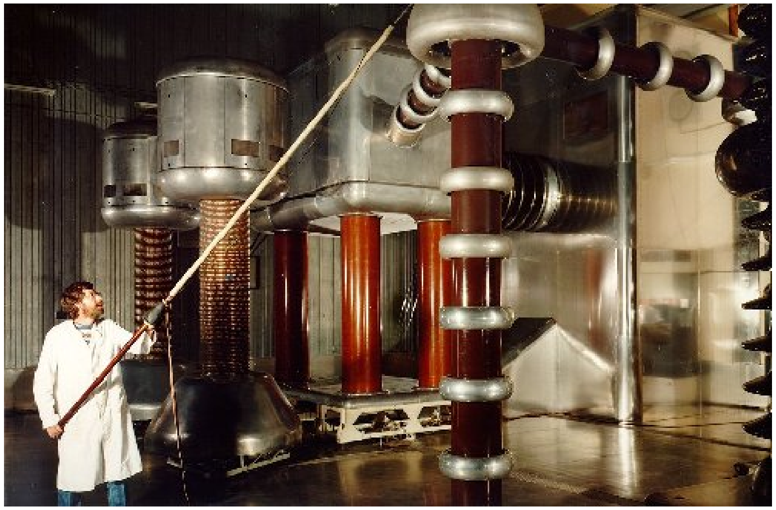
ISIS: a 200-300 μA Neutron Source

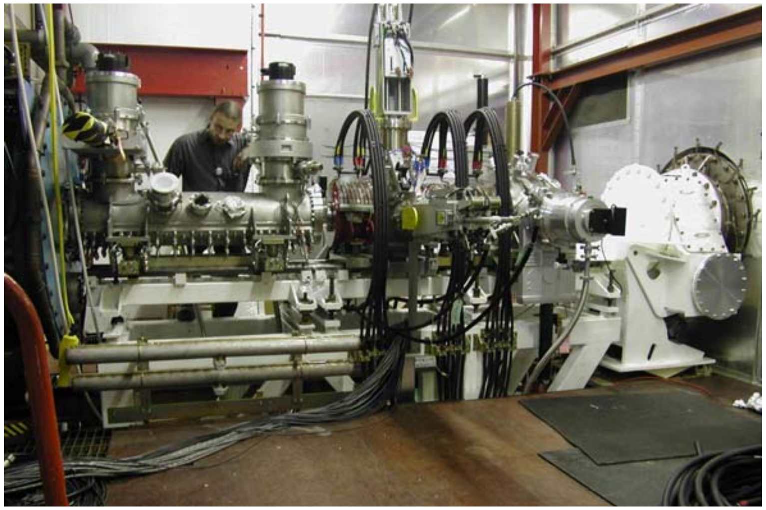


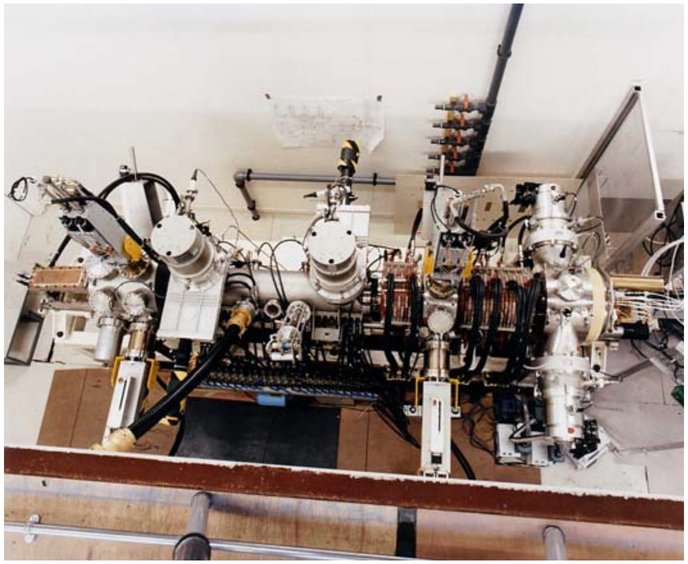
Serves as benchmark for development of other spallation neutron sources: SNS, ESS, facilities in China, studies in India.

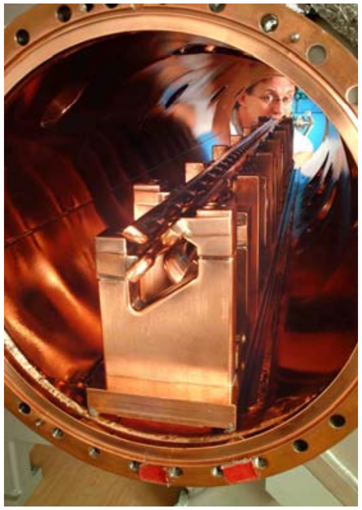
- 70.4 MeV H- linac feeding an 800 MeV rapid cycling synchrotron operating at 50 Hz
- Mean ring radius R_0=26 m
- Charge-exchange injection with Al_2O_3 stripping foil
- ~10% beam loss in first 1 ms of cycle
- 2 bunches each of ~120 ns duration at tantalum-clad tungsten target.
- 200 μA of beam current, ~160 kW beam power. ←2002
- Injector recently upgraded with addition of a Radio-Frequency Quadrupole.
- Combined h=2/h=4 RF system installed to upgrade machine to ~300 μA, 240kW
- £140 m approved for new 10 Hz target station (under construction).

Radio Frequency Quadrupole (RFQ)


Old Cockcroft-Walton pre-injector


RFQ complete assembly with vacuum pumps and solenoids



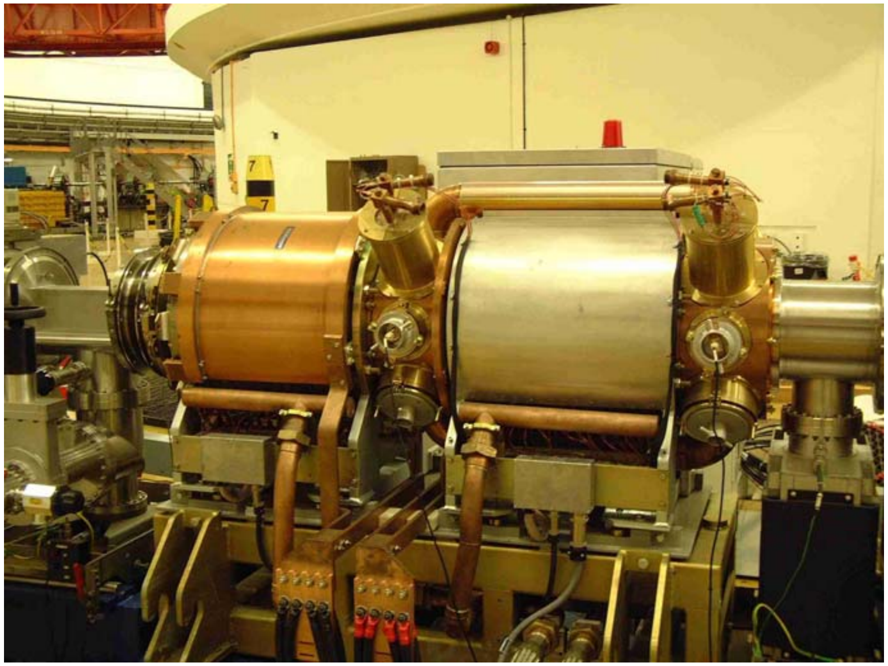


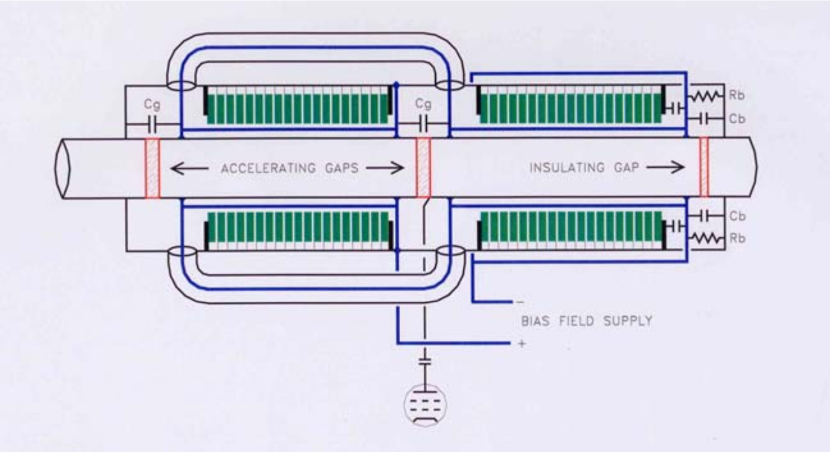
Dual Harmonic RF Accelerating System

- 4 new h=4 cavities to supplement 6 existing h=2 cavities (RAL-KEK-ANL collaboration)

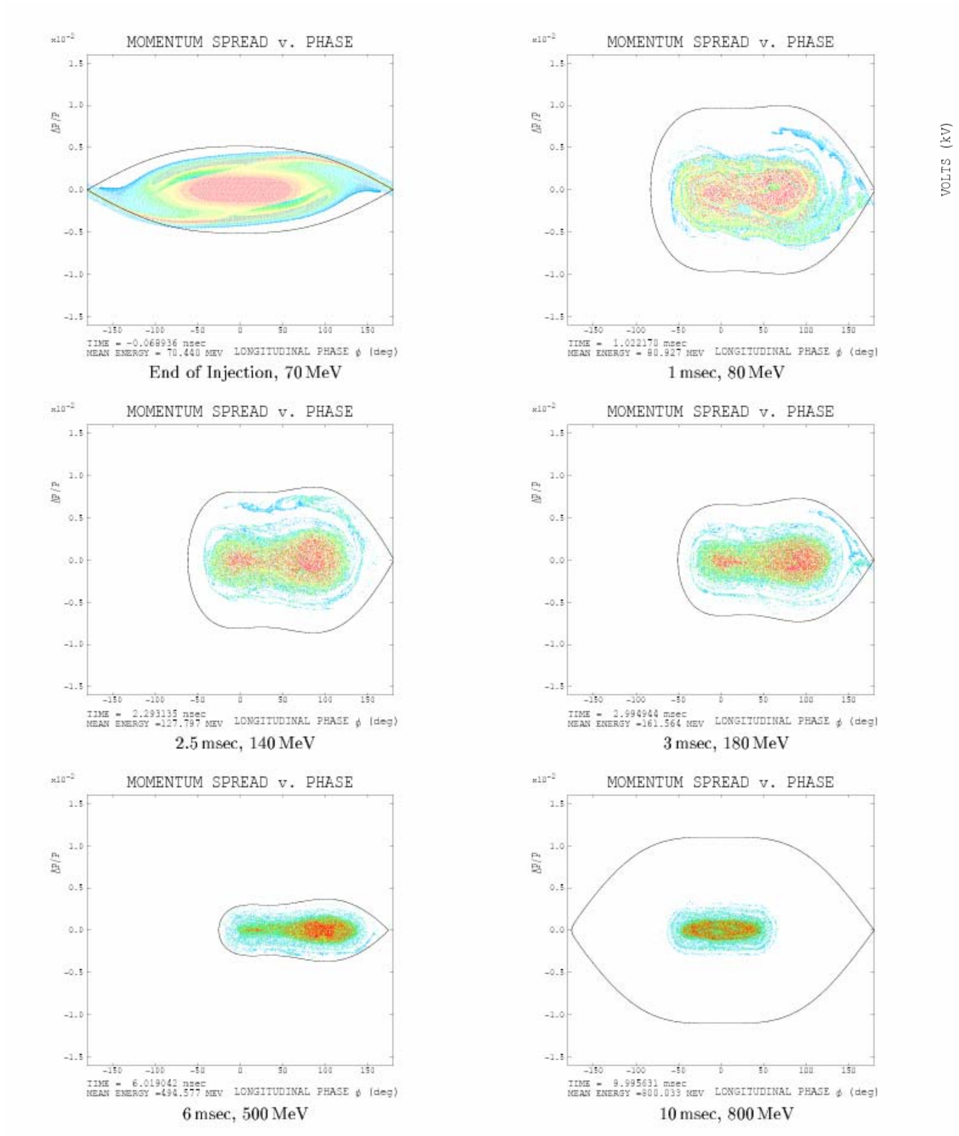
$$V(\phi,t) = \hat{V}(t)\left[\sin\phi - \delta\sin\left(2\phi + \vartheta\right)\right]$$

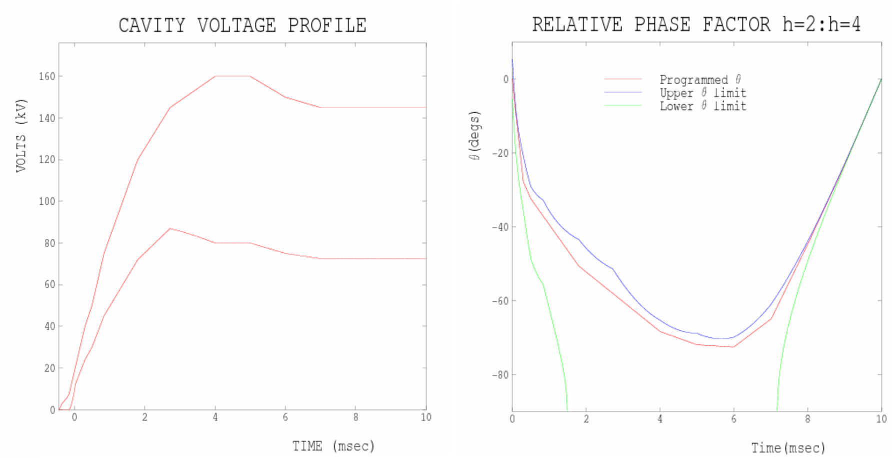
- Ratio of h=2:h=4 voltages δ varied with time.
- Relative phase θ varied with time.
- Gives increased stable region in longitudinal phase space.
- Increases bunching factor and allows injection of more particles without increase in level of space charge.





Dual Harmonic RF: Simulation of 3 $\times 10^{13}$ ppp





Simulation show ~0.5% beam loss during injection and trapping; some very small loss (<0.1%) at about 3-4 ms (~200 MeV).

Designed for 10-20% increase in intensity but improvement in bunching factor suggests could increase by 50%:

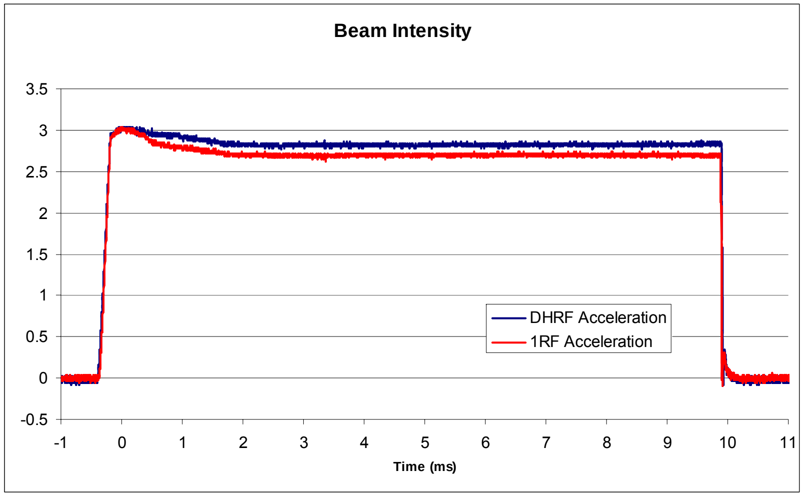
160 kW → 240 kW

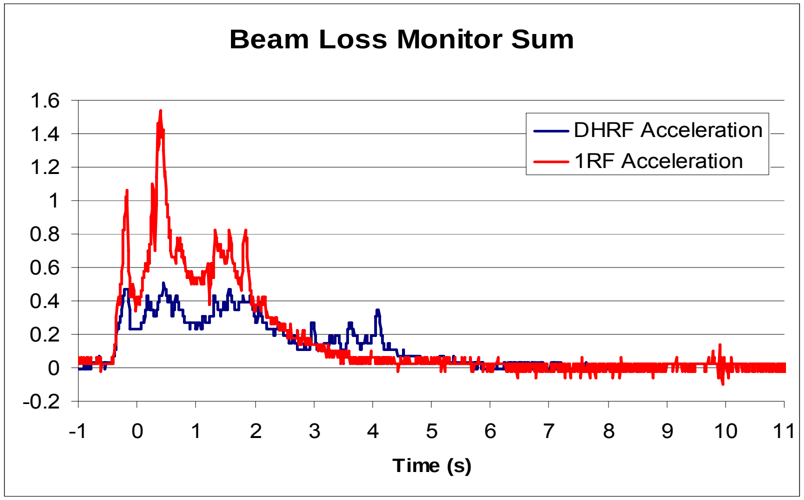
November 2006

- ISIS running with only two of four h=4 cavities in operation.
- Settings for single harmonic cavities as for normal ISIS operation.
- Does not correspond to dual harmonic design specifications.

Nevertheless:

- Beam losses more than halved — 97% transmission: highest trapping efficiency ever achieved.
- Note small loss at 3-4 ms



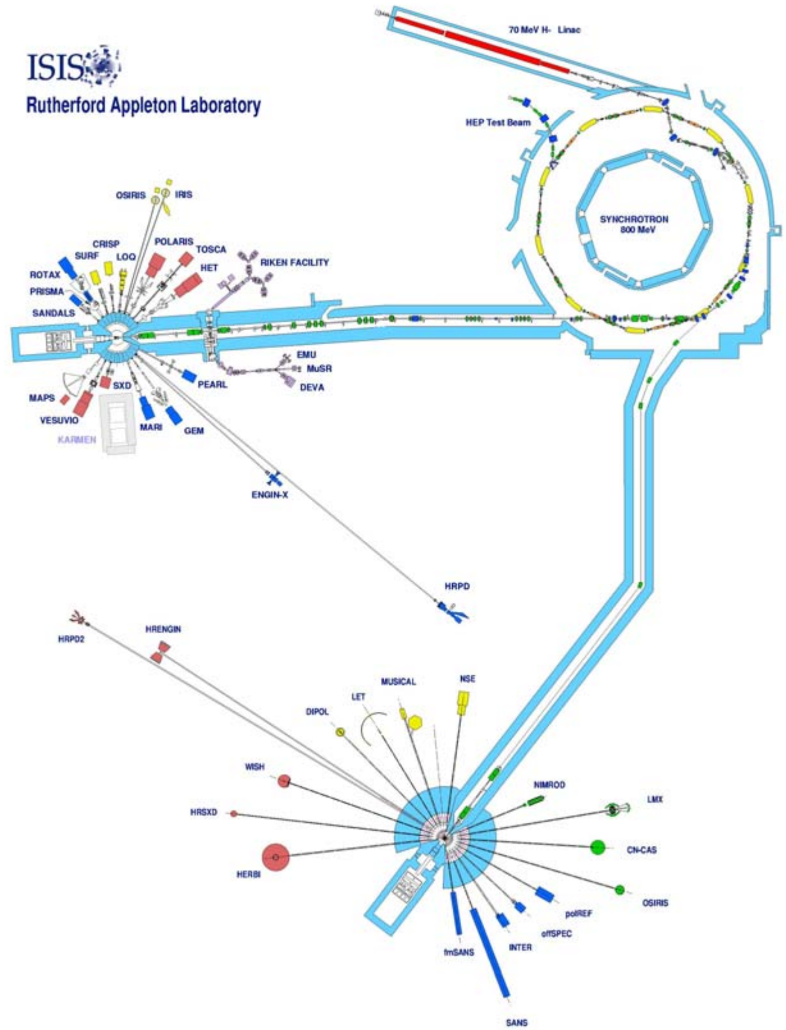


Restoration of Status Quo

Unoptimised system exceeds 200 μA, giving confidence in sizeable increase when remaining h=4 cavities are switched in and correct settings are in place.

ISIS Second Target Station Project (TS2)

- Major investment to extend capability and capacity of ISIS to meet future scientific needs in key areas of:
  - Soft Matter
  - Advanced Materials
  - Bio-materials
  - Nano-technology
- New 10 Hz target station, TS2
  - takes one pulse in five from ISIS synchrotron to handle the increasec ISIS beam power.
- Low power:
  - 48 kW power
  - 60 μA current
- Design optimised for cold neutron production



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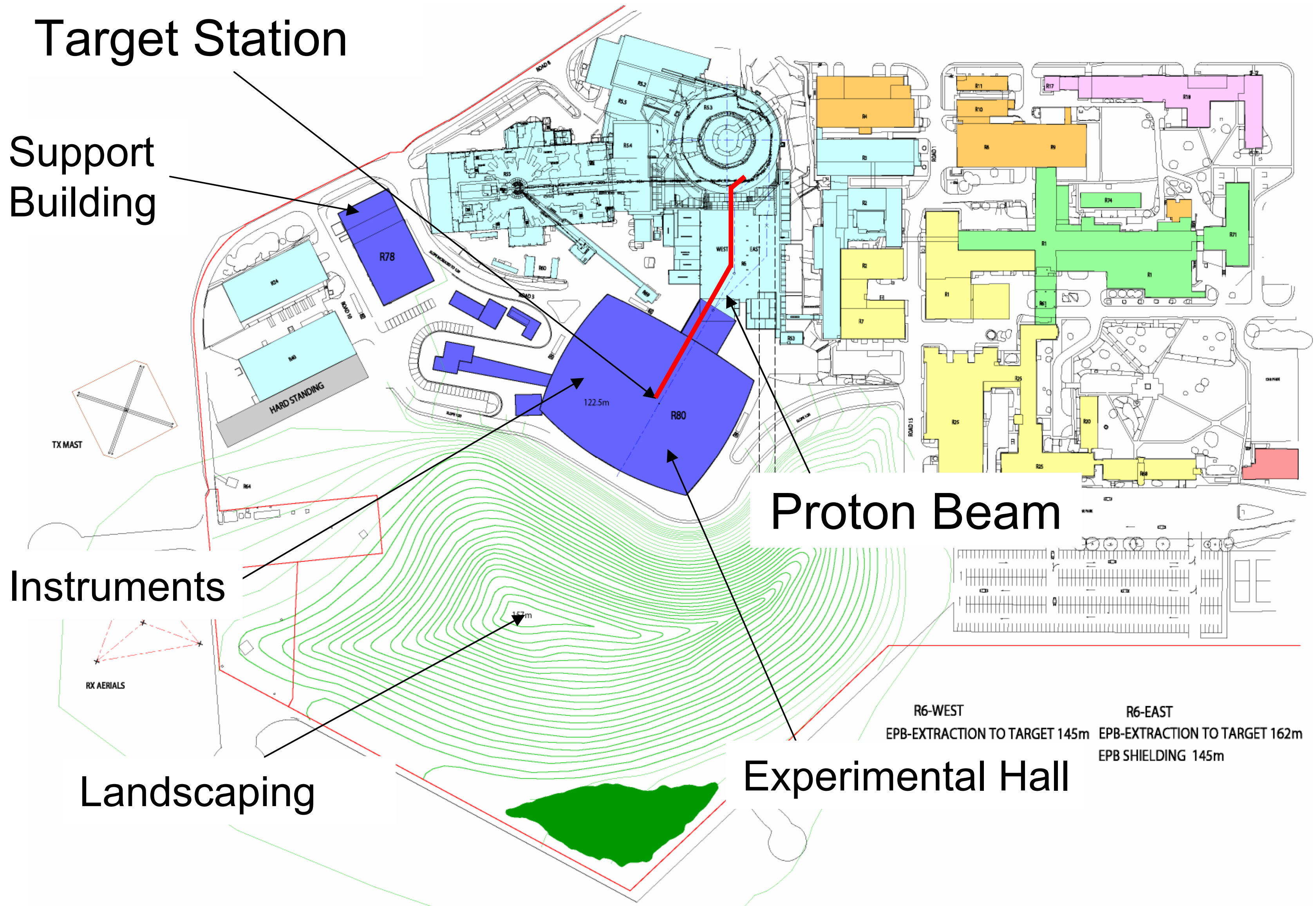
ISIS Second Target Station Project



TS2 Experimental Hall

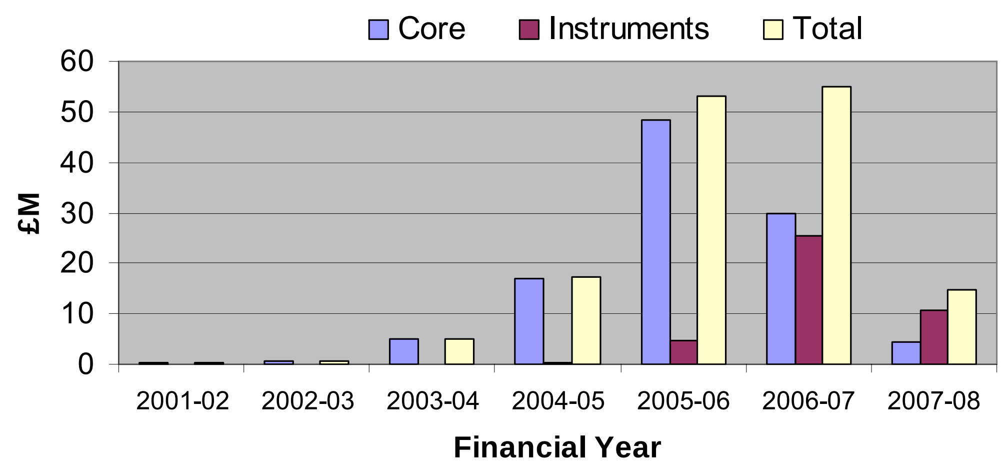
TS2 Project Milestones

April 03	DTI announcement of funding for project
Sept 04	Building structure complete
Oct 06	Buildings complete
Sep 07	EPB, Target station complete
Oct 07	1st proton beam to target
Nov 07	1st Instrument operation
June 08	Complete instrument installation
Oct 08	Start user programme

Buildings	£32M
Proton Beam	£31M
Target Station	£30M
Contingency	£10M
Instruments	£40M

Operating cost ~ £5 - 8M per year

ISIS Second Target Station Spend Profile



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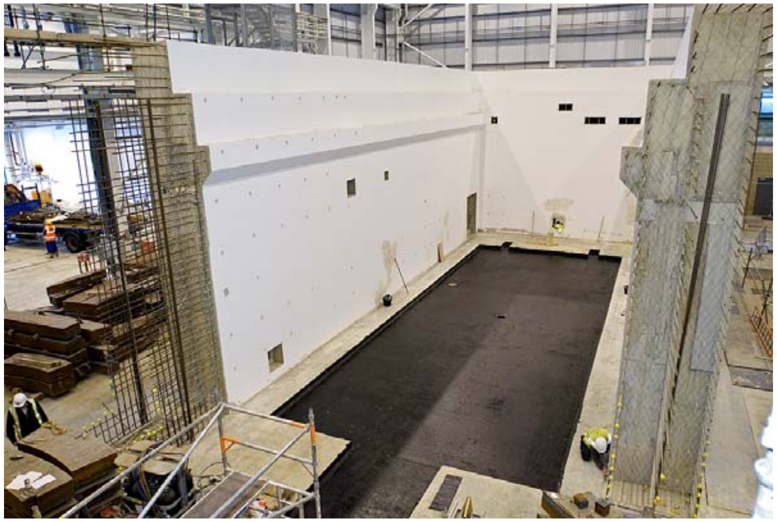
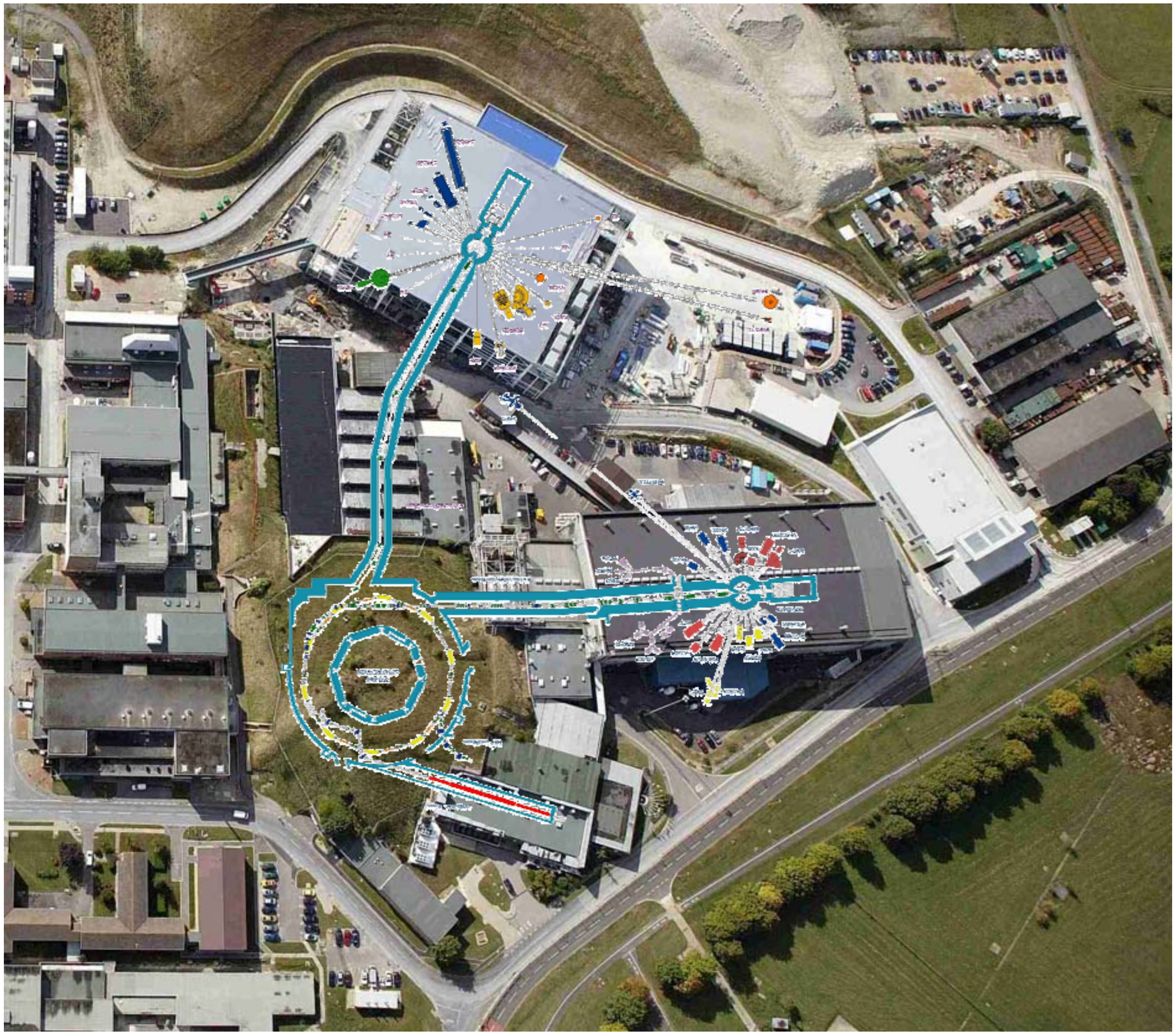
TS2 Target Station Monolith Construction

TS2 Target Station and Services Area Construction

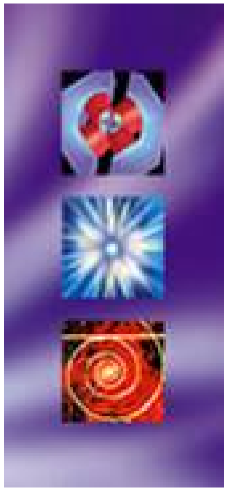
TS2 Target Station and Services Area Construction



ISIS 2007



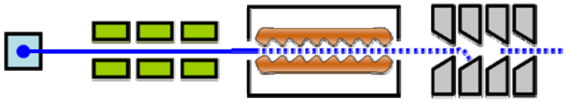
Generic R&D



Motivation from studies for

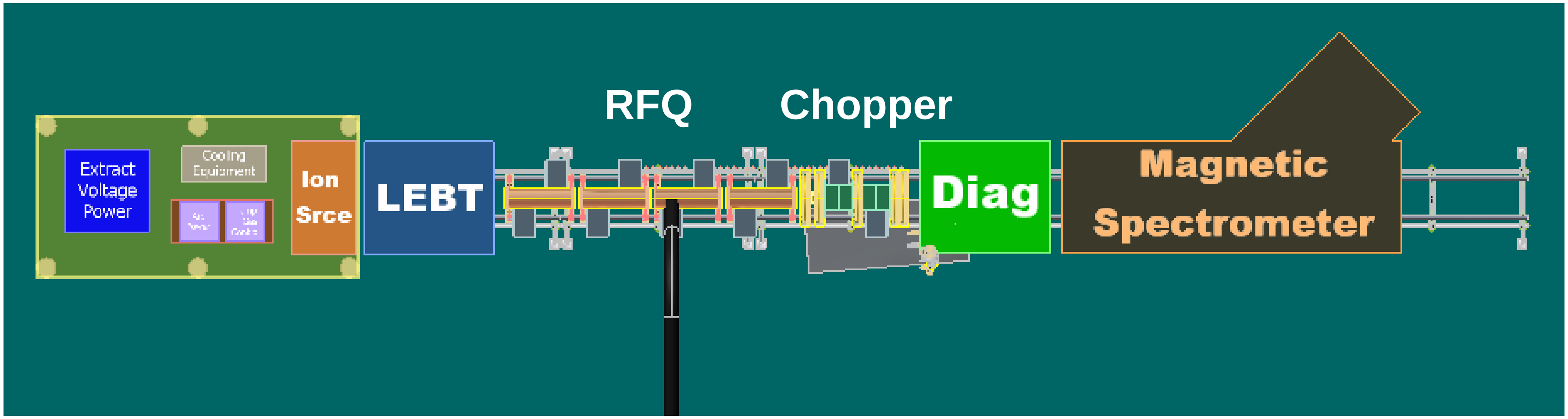
- Spallation Neutron Sources (ESS, SNS)
- Proton drivers for a Neutrino Factory
- Proton driver at Fermilab

Front End Test Stand (FETS)



FETS main components:

- High brightness H^- ion source.
- Magnetic Low Energy Beam Transport (LEBT).
- High current, high duty factor Radio Frequency Quadrupole.
- Very high speed beam chopper (3 MeV).
- Comprehensive diagnostics.



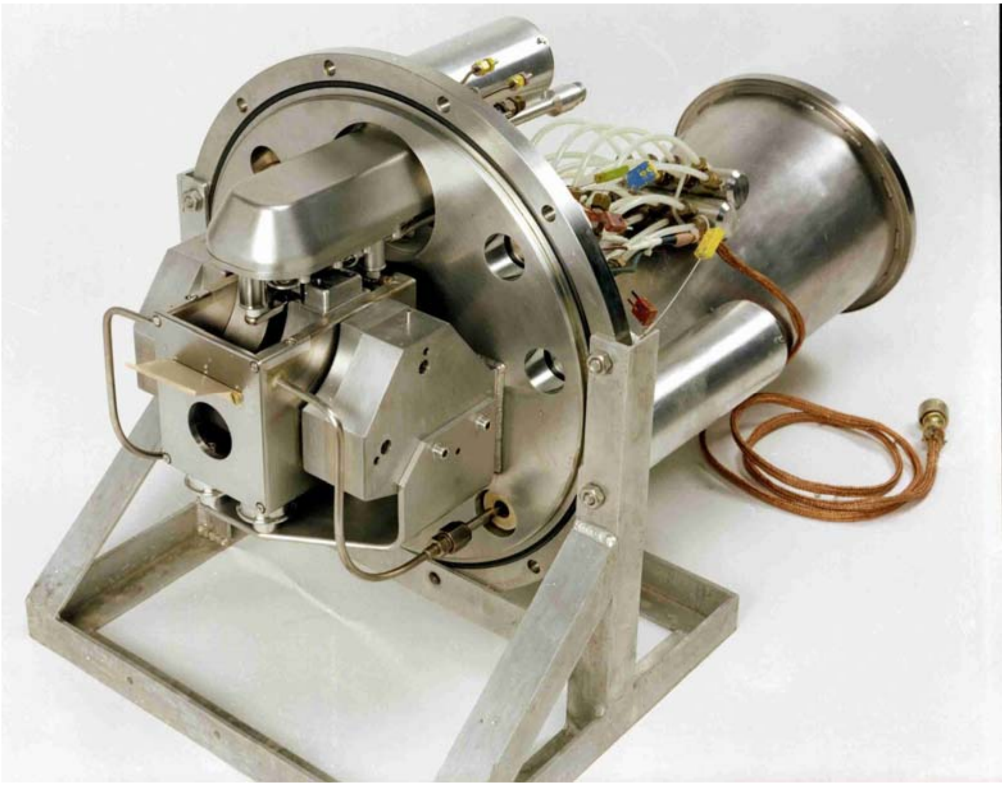
Ion Source

Present operation:

- Penning H- ion source
- Surface Plasma Source
- 35 mA through 0.6×10 mm aperture (≈ 600 mA/cm2)
- 200-250 μs, 50 Hz, ~1% duty cycle
- 0.17 π mm mrad (@ 665 keV, 35 mA)

Goals:

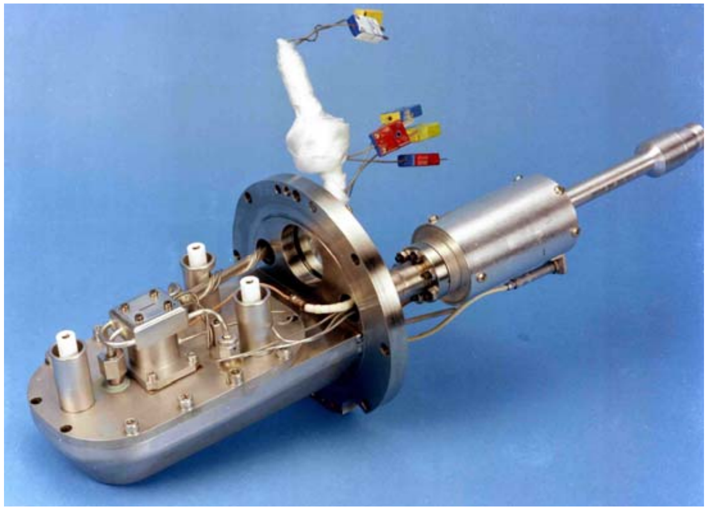
- Double output current:
  35 mA → 70 mA ☑
- Increase pulse length:
  200 μs → 2 ms ☑
- Improve emittance
  ε_{nrms}=0.2 π mm.mrad
- Maximize lifetime ≥10 weeks



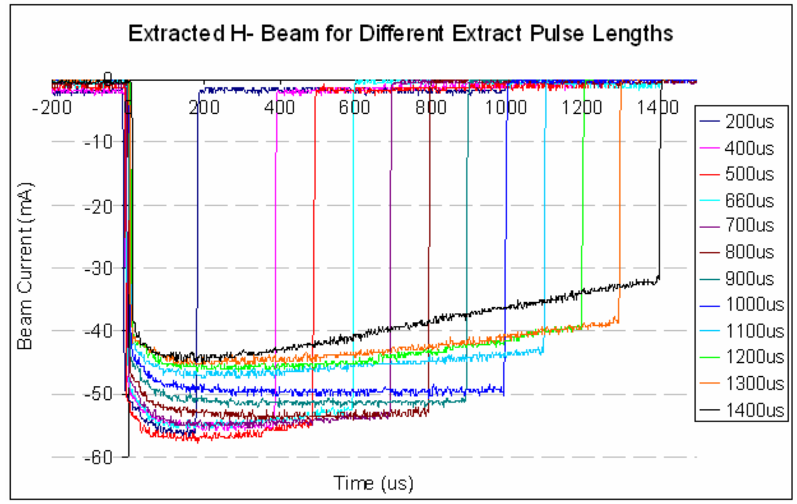
Ion source development: complete assembly

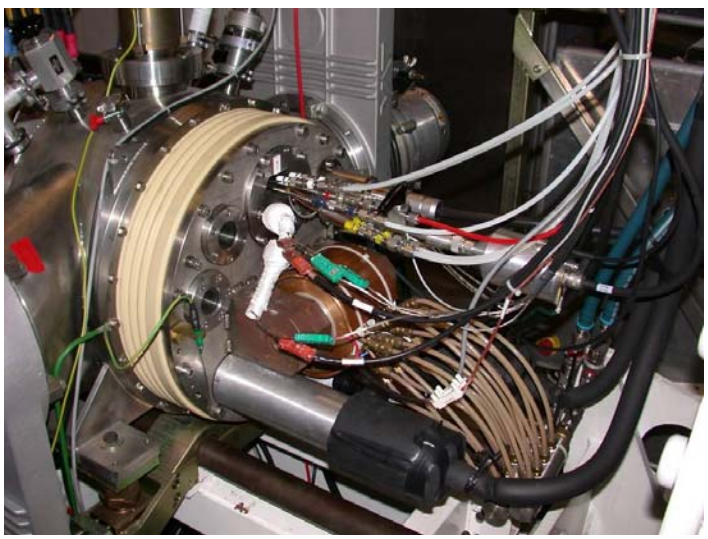
Improved extraction geometry; addition of a separate Penning field magnet

Ion Source Development

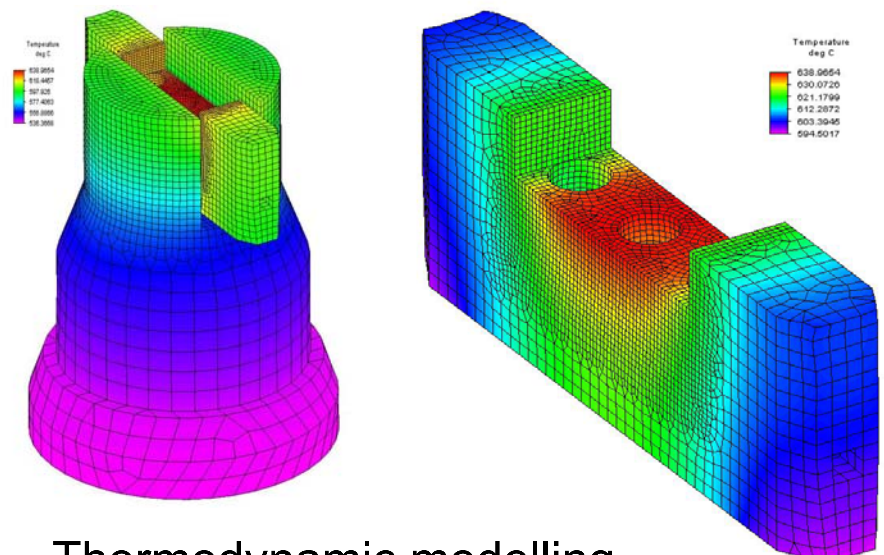


Ion source, without extraction electrode





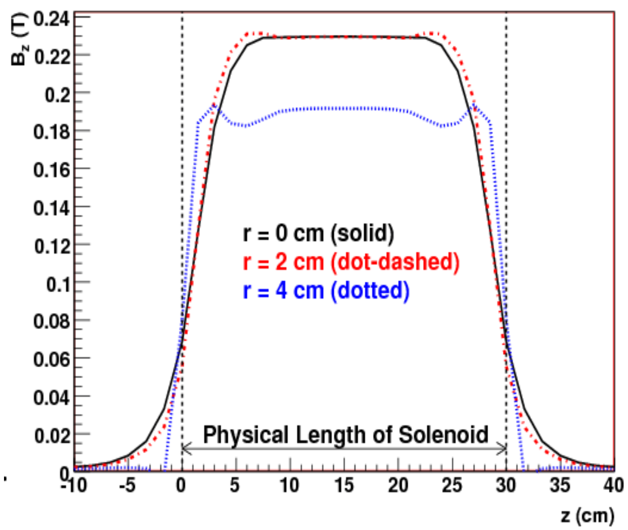
Ion source fitted on RFQ assembly



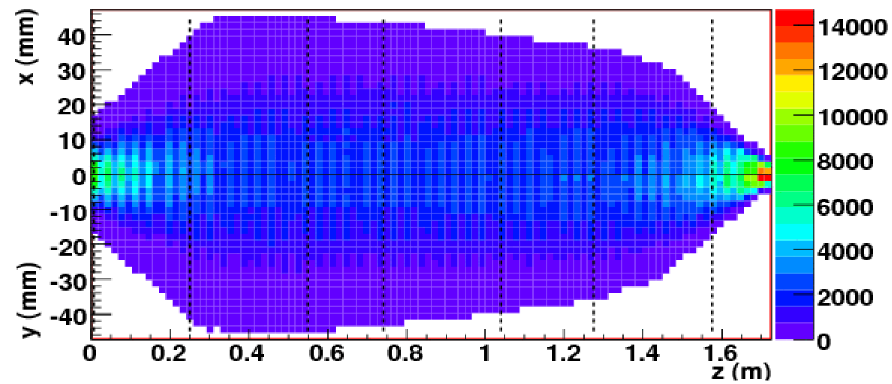
Thermodynamic modelling

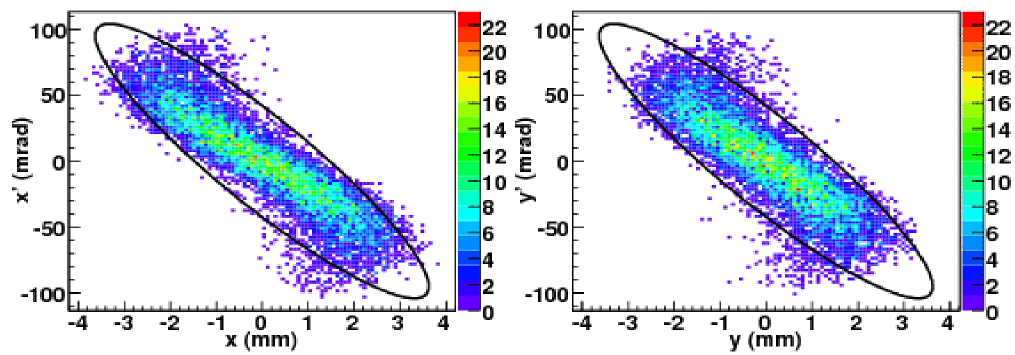
Low Energy Beam Transport

- A 3 solenoid magnetic LEBT is being designed, based on the successful ISIS RFQ injector.
- An electrostatic LEBT has been rejected due to the close proximity of the caesiated ion source.
- Optimisation of the magnetic design is near completion



First simulations used an idealised beam of the required emittance based on ISIS LEBT measurements.

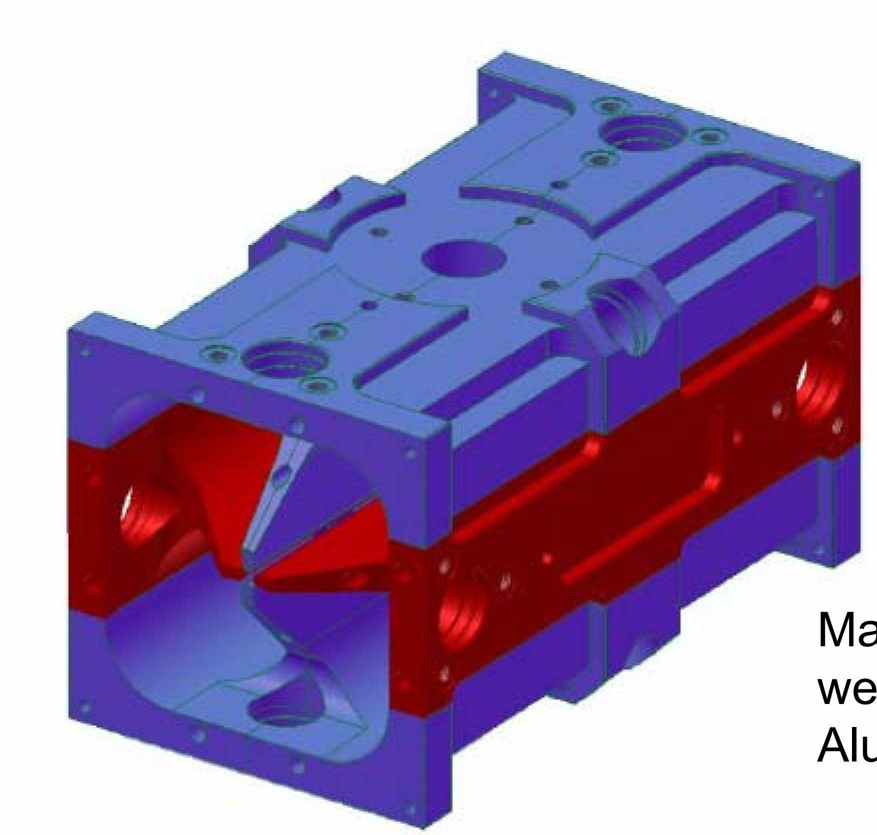


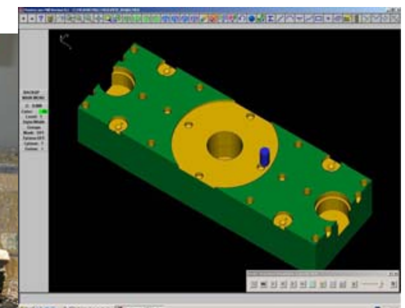


($\varepsilon_{x,rms}$=0.33 π mm.mrad; $\varepsilon_{y,rms}$=0.33 π mm.mrad)

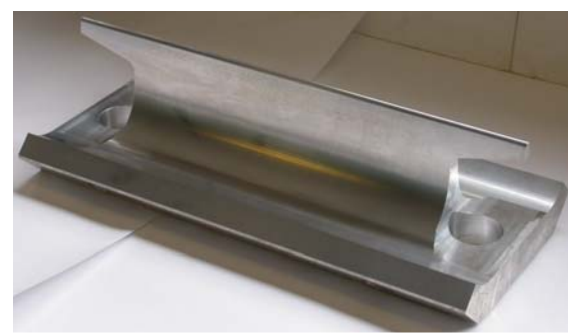
FETS: 324 MHz Radio-Frequency Quadrupole

- Initial beam dynamics design completed for a 324 MHz RFQ.
- Shows negligible emittance growth; 94% transmission for an ideal 60 mA beam.
- A 0.5 m, 324 MHz 4-vane RFQ cold model is almost complete. The cold model designed contains all the significant features of the final 4 m long design.

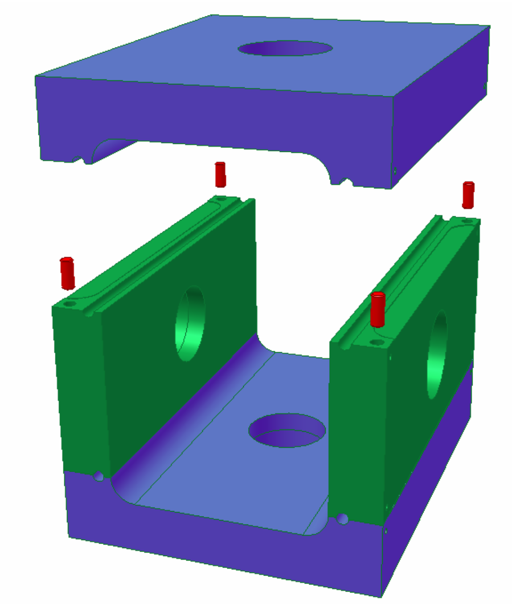




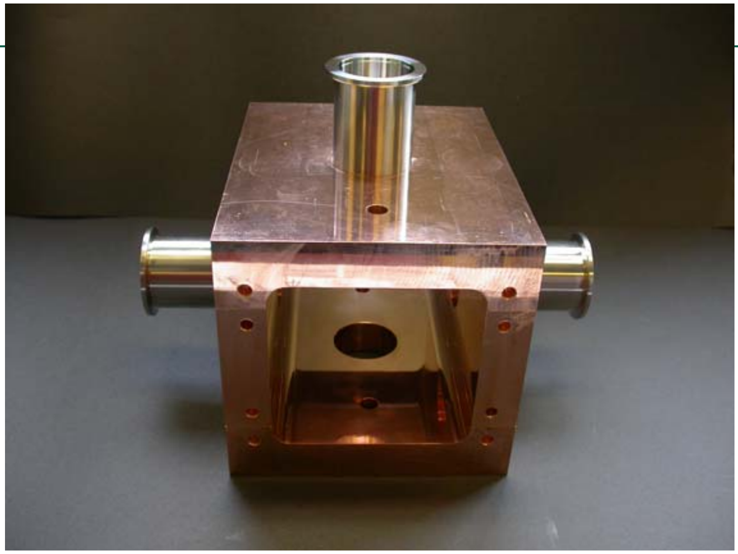
Machining operations were tested in Aluminium initially

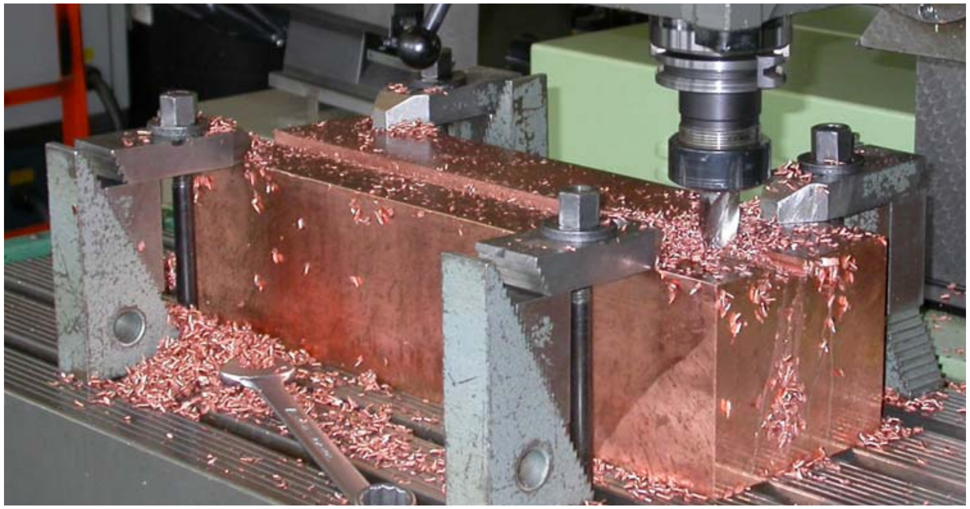


FETS: RFQ Cold Model



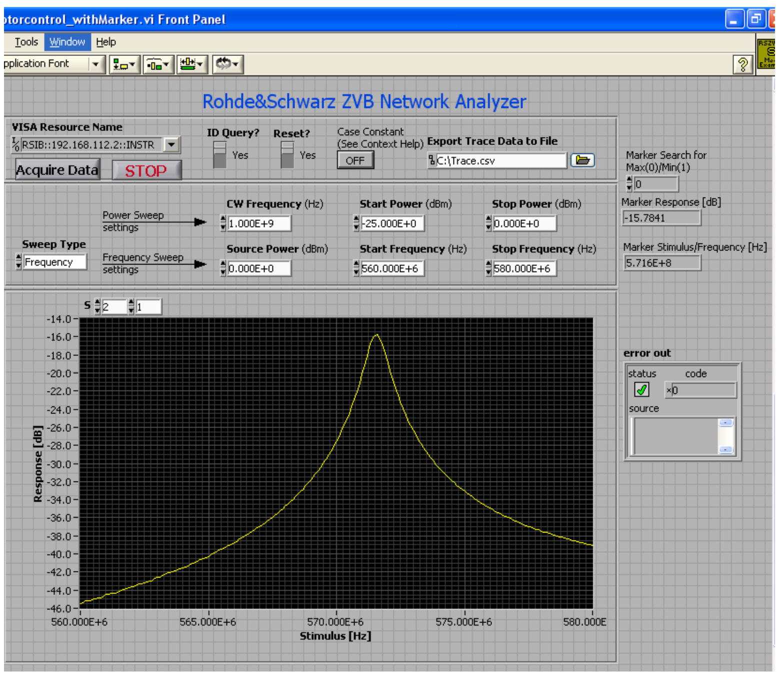
A braze test piece has been completed

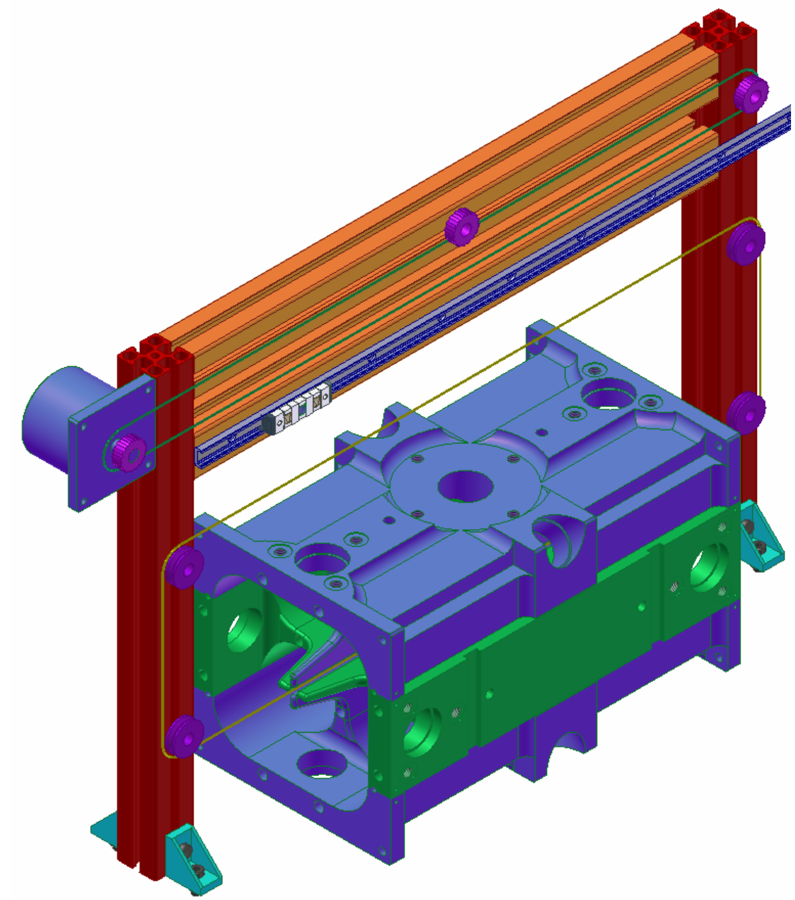




FETS: Cavity Field Measurements

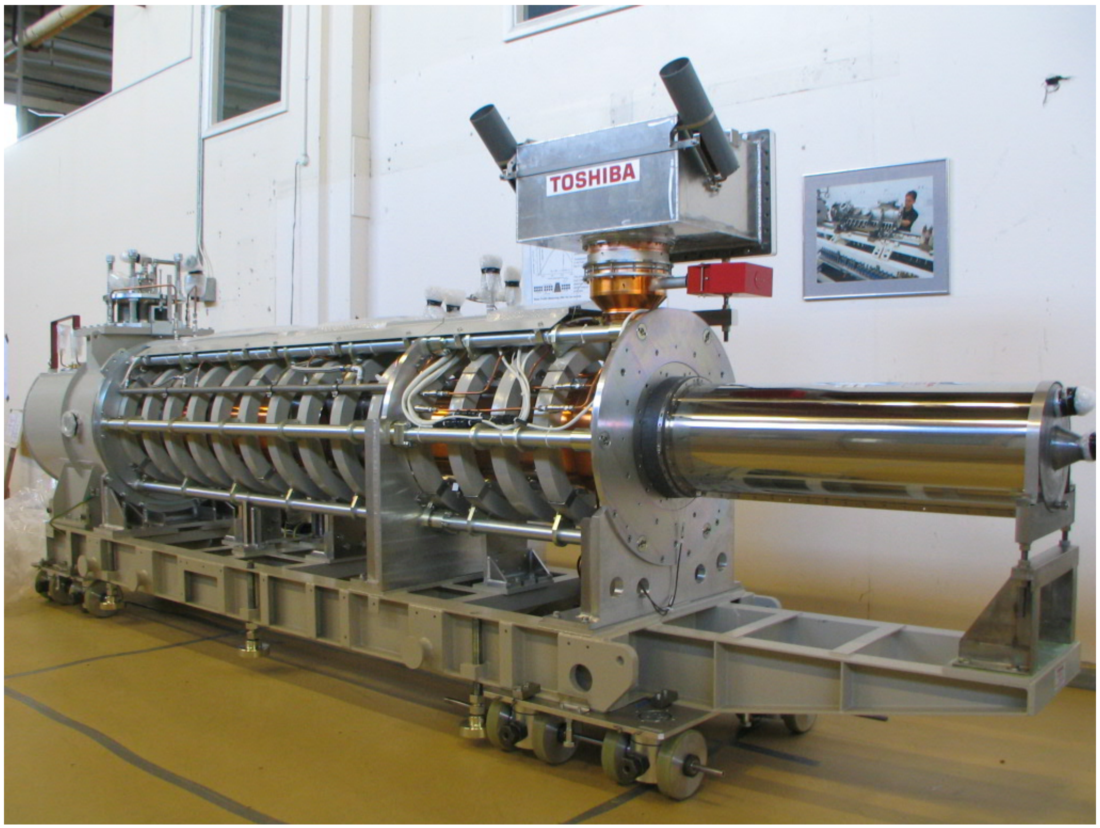
A computer controlled bead pull perturbation system is under development to perform cavity field measurements on the cold models

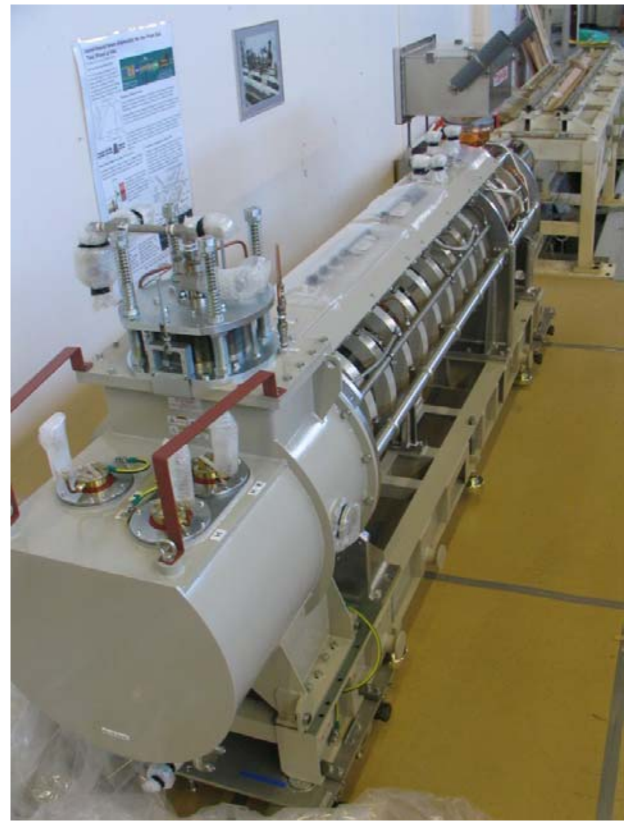




FETS: High Power Klystron

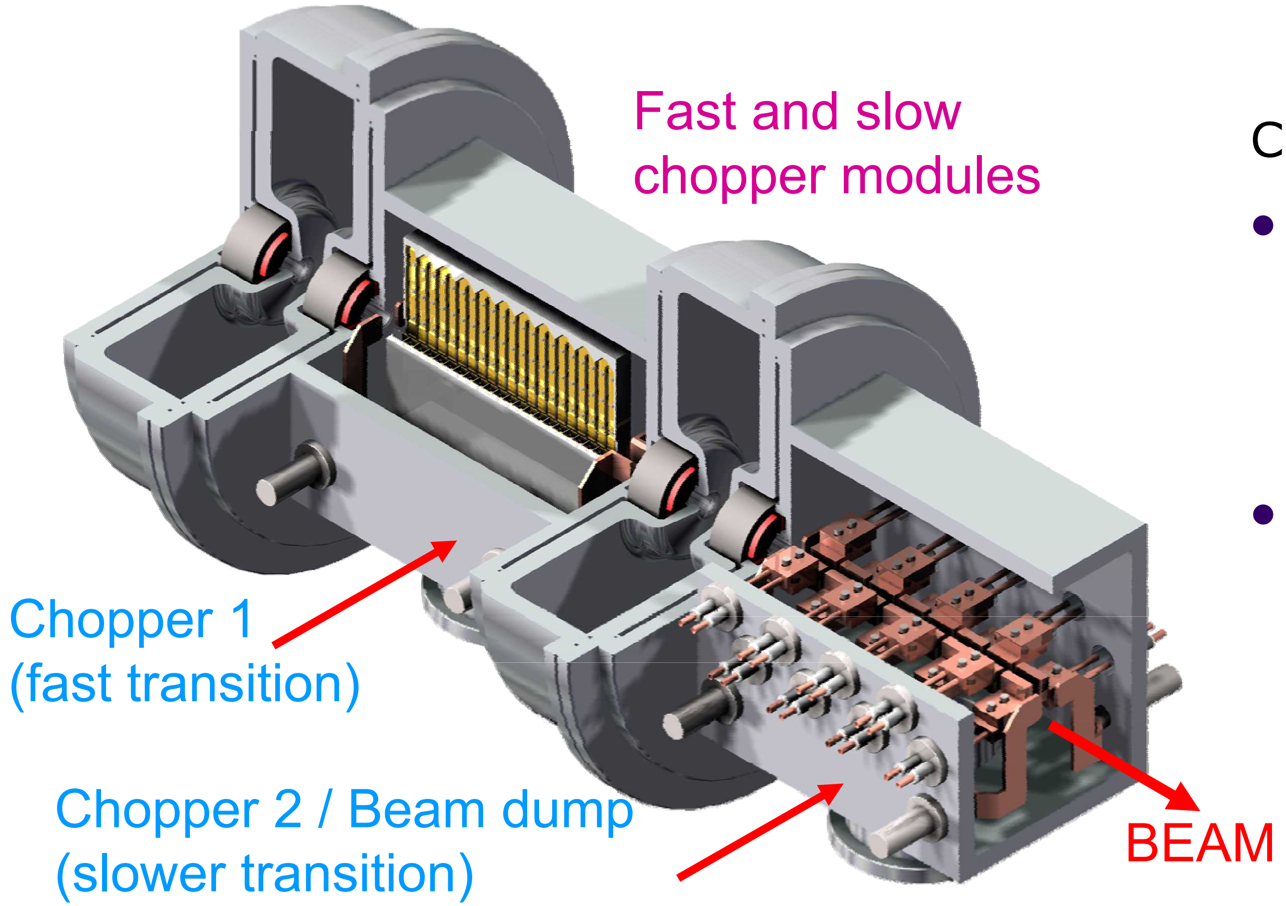
A Toshiba E3740A 2MW high power pulsed klystron has been delivered.
European tender started for klystron PSU.





Fast Beam Chopper

A novel tandem chopper technique has been developed at RAL to overcome the conflicting requirements of fast rise time (< 2ns) and long flat-top (up to 100 μs).

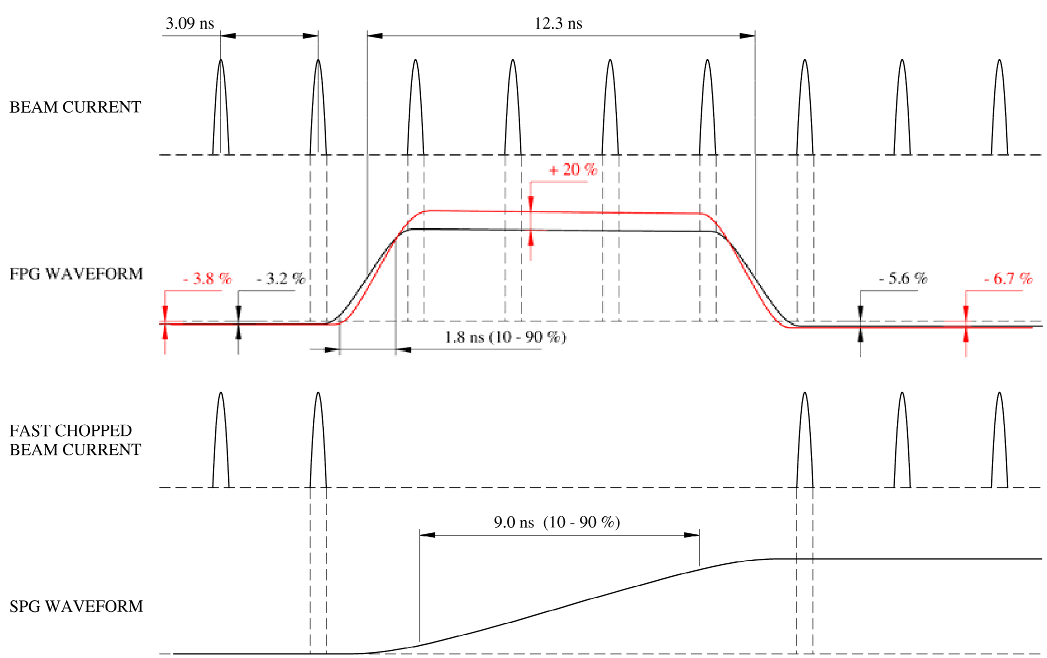


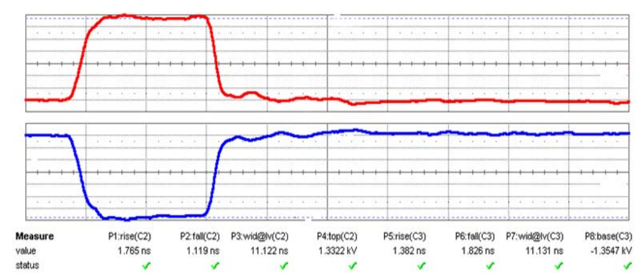
Chopping facilitates

- very low loss ring injection (10^{-4}) for hands-on maintenance.
- provides a gap for the ring extraction kickers to come on.

FETS: Fast Beam Chopper

- A ‘fast’ chopper removes 3-4 microbunches to create a short, clean gap in which the field of a ‘slow’ chopper can rise.
- The fast pulser is limited in flat-top but can switch between bunches.
- The slow pulser has a longer rise time but can generate the required flat-top.
- The system operates in reverse after chopping is completed.





A state of the art fast switch developed for RAL has achieved ±1.4 kV, 15 ns flat top, with rise and fall times less than 2 ns.

Slow chopper has met all specifications except for required duty factor

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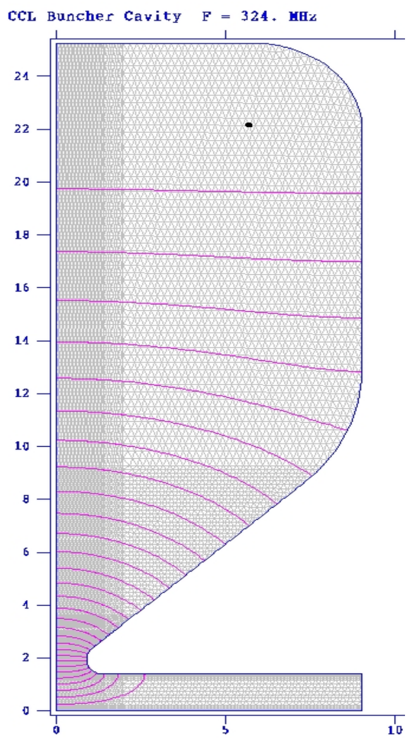
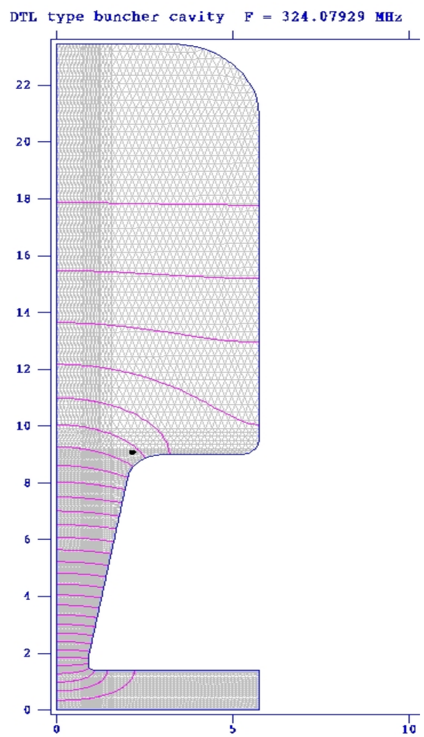
FETS: Chopper Buncher Cavities and Quadrupoles

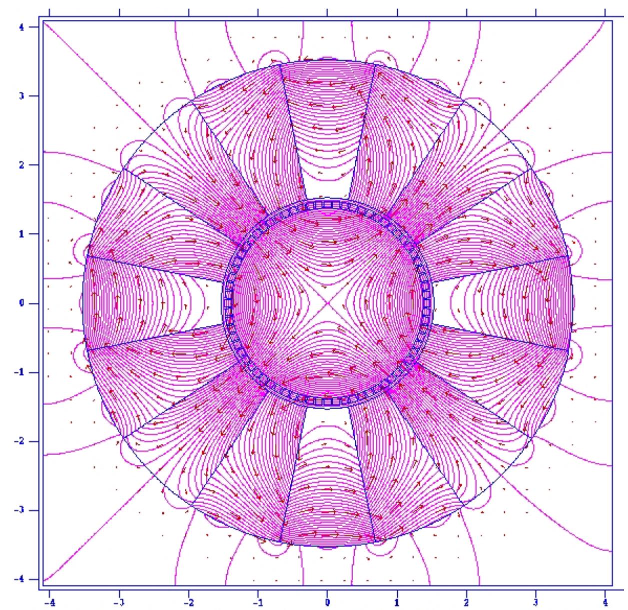
The shortest solution will require novel, compact, high gradient quadrupoles and DTL-like cavities.



CCL type cavity



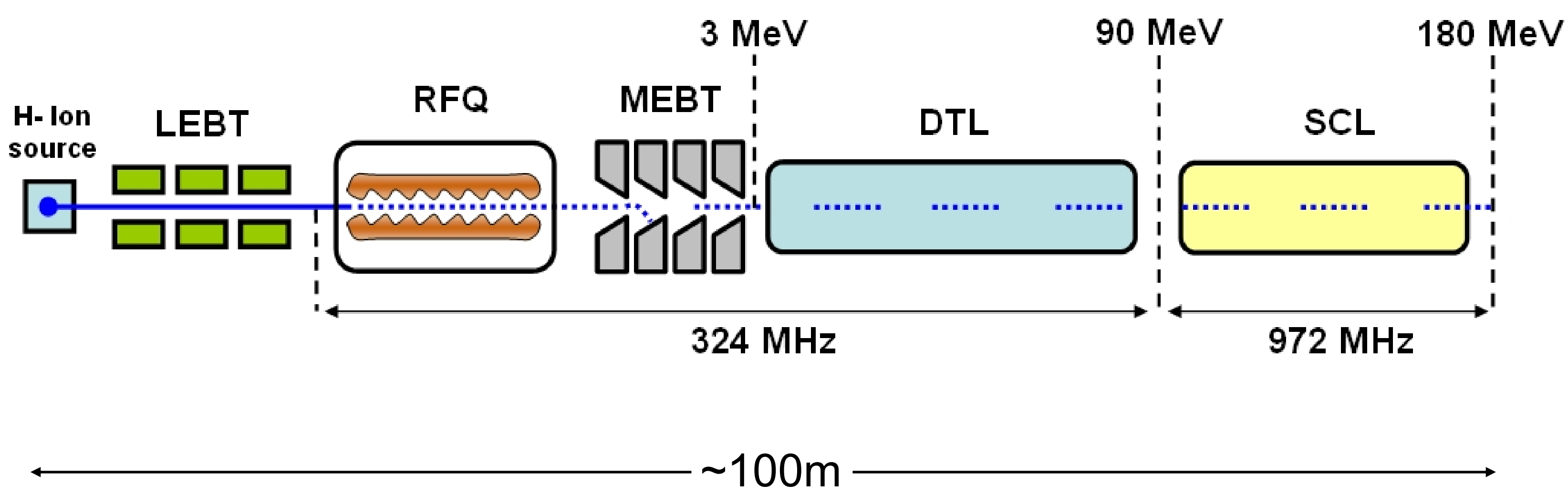
DTL type cavity



Hybrid PM and EM quads are being investigated.

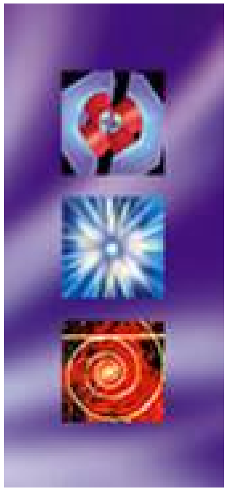
High Current 180 MeV H^- Linac Studies

- An H^- linac to ~200 MeV is common to all RAL proton accelerator designs, whether for neutron generation or as the driver for a muon-based neutrino factory.
- RAL's work progresses in parallel with similar studies at CERN for Linac4 (recently approved for construction).



ISIS Upgrades

→ ½ →1→2→5 MW

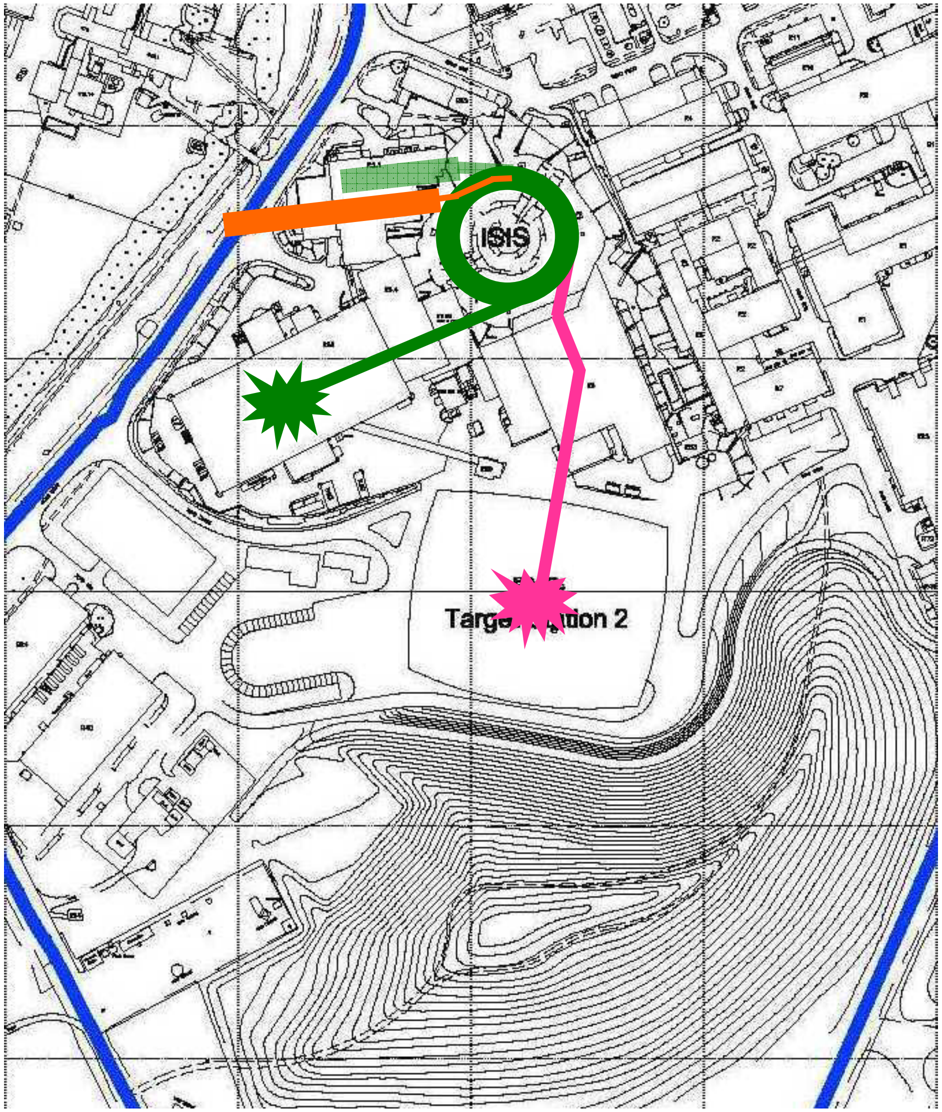


½ MW Upgrade I

- Replace existing 70MeV linac with new injector.
- Injecting at 180 MeV halves the space-charge tune depression and allows more beam to be accelerated.
- Present injection geometry, some upgrades to ring (RF); use existing target station?
- Could increase repetition rate to 64 Hz with same peak RF voltages.
- Significant power increase

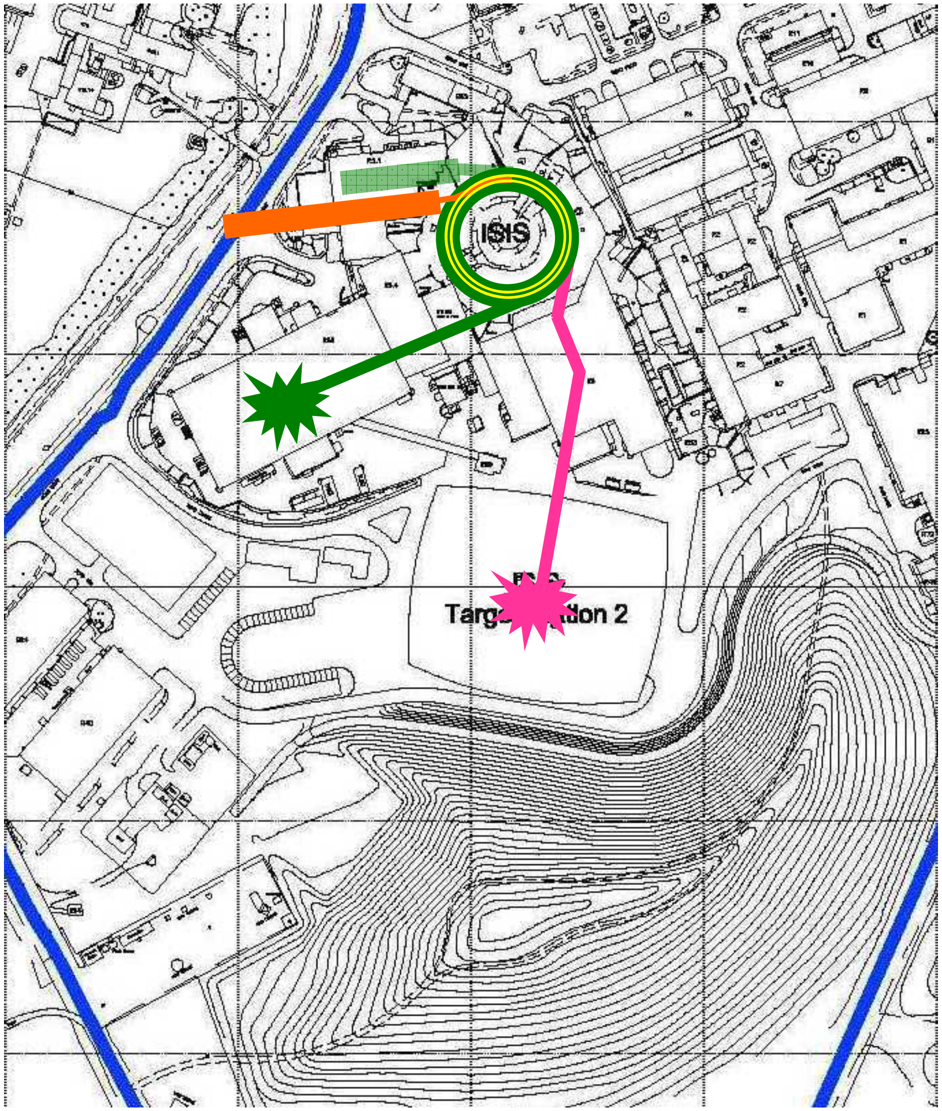
  240 kW → ~500 kW
- 2 bunches per pulse each of 3.75×10^{13} protons
- Advantage of replacing old equipment and good potential for future upgrades.

BUT: target station is certainly limited to ½ MW and may not take more than ¼ MW



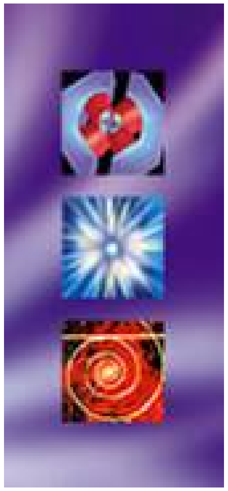
½ MW Upgrade II

- Build a new 800 MeV ring in present synchrotron tunnel.
- Inject 2 extra bunches
- Doubles beam power
- Better with new 180 MeV linac
- 4 bunches per pulse each of ~1.85×10^{13}
- May be construction difficulties in ISIS tunnel.

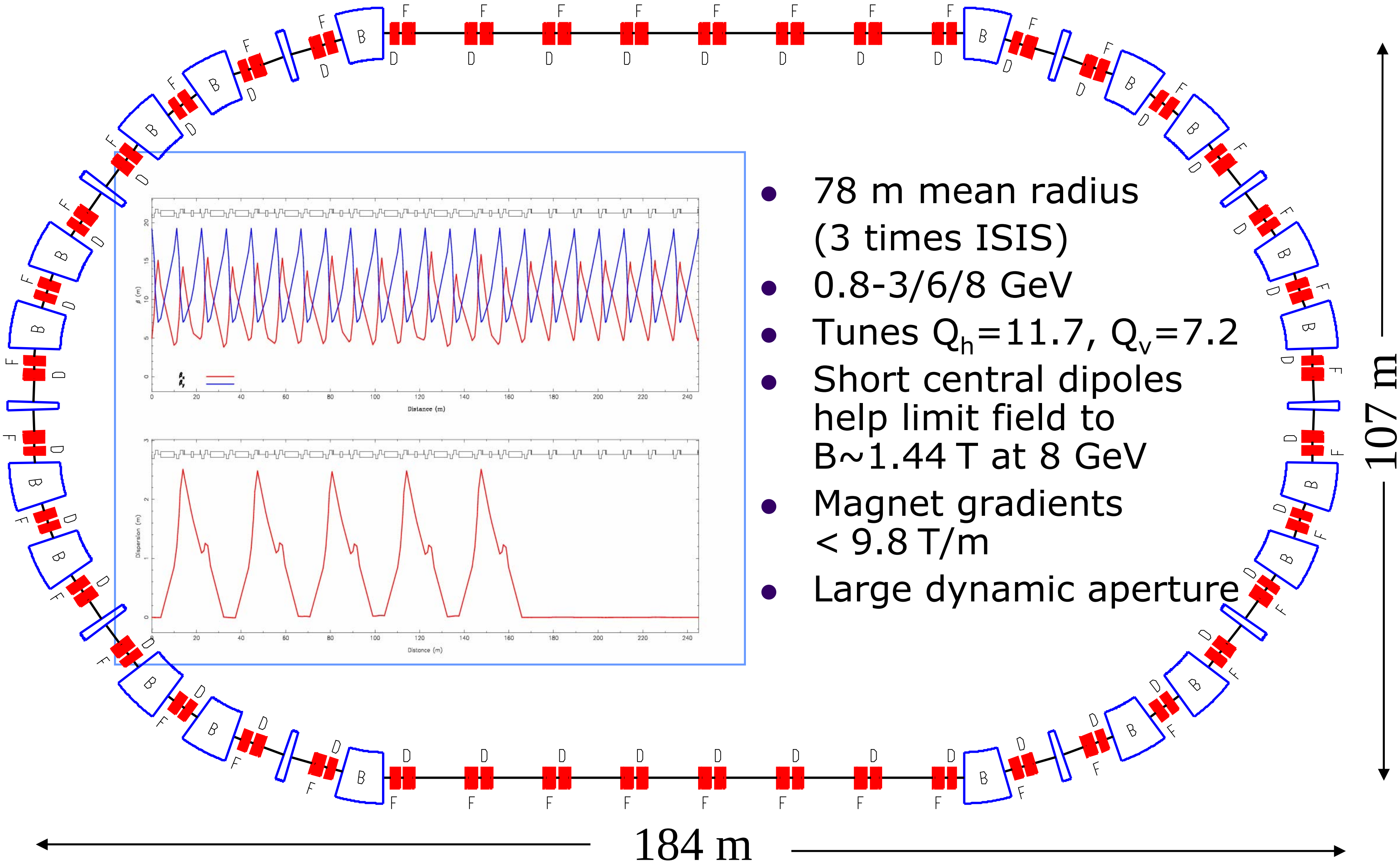


Upgrades to 1 MW and above

- ISIS space charge limited
- Solution lies in new rings and higher energy
- Requires new target station(s)
  - Cost does not rise in proportion
  - Significantly more expensive
- Raise energy to ~3 GeV required for 1 MW



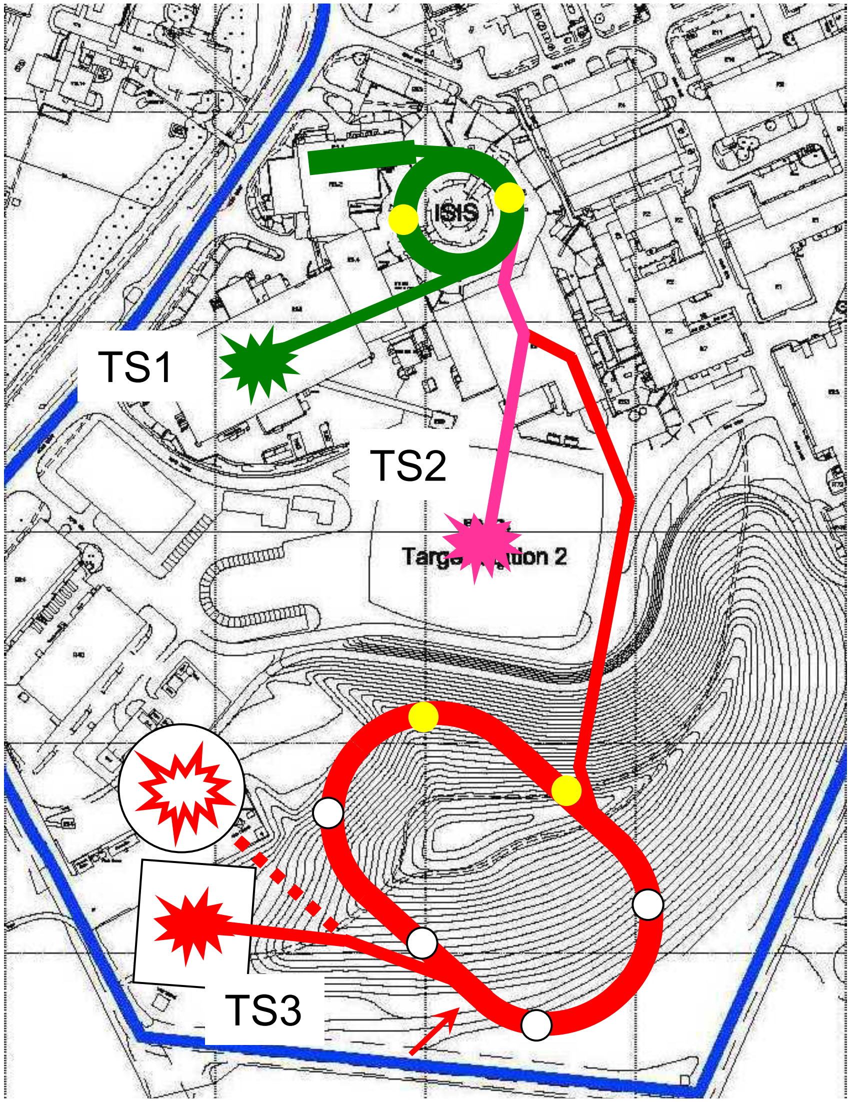
New Synchrotron



- 78 m mean radius (3 times ISIS)
- 0.8-3/6/8 GeV
- Tunes Q_h=11.7, Q_v=7.2
- Short central dipoles help limit field to B~1.44 T at 8 GeV
- Magnet gradients < 9.8 T/m
- Large dynamic aperture

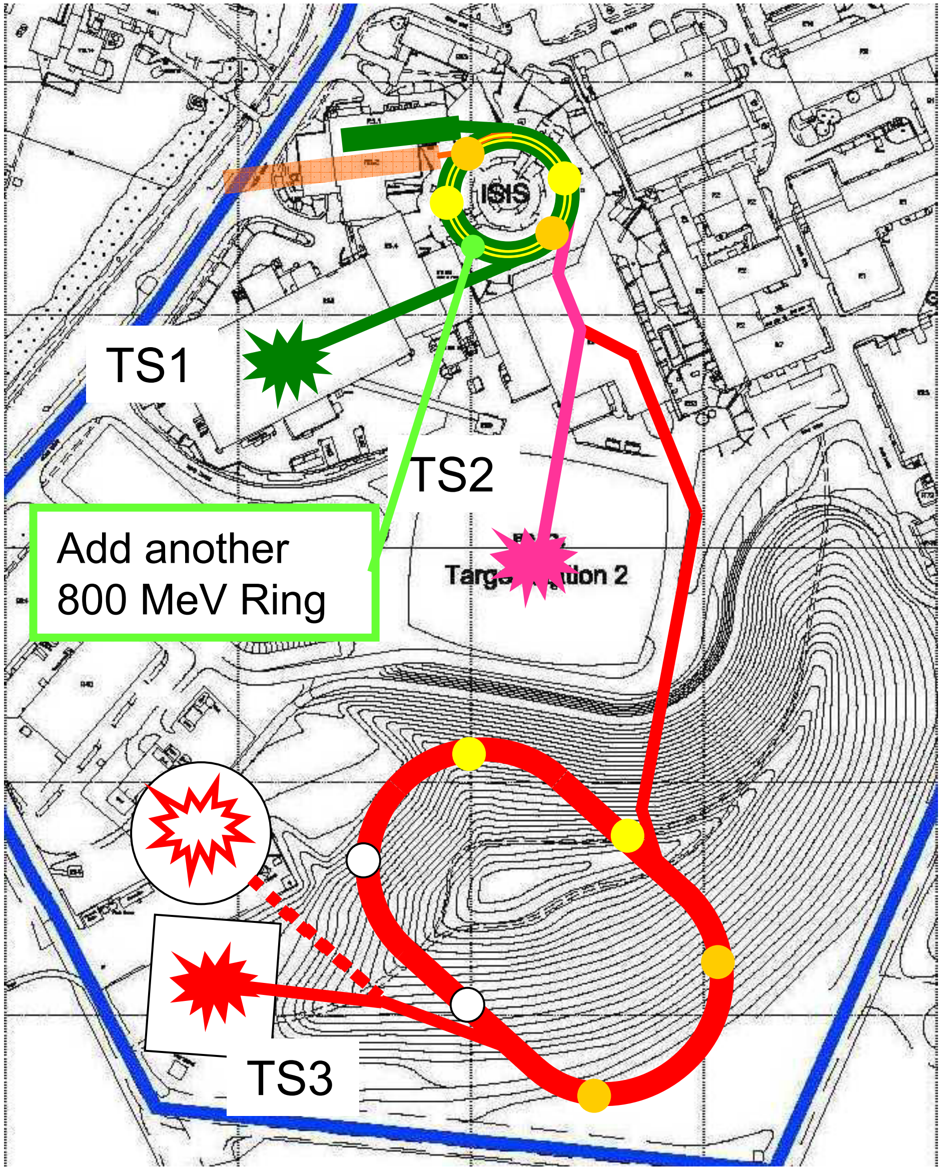
1 MW Upgrade with New Synchrotron I

- One new synchrotron ring.
- New target station TS3 designed for ≥1 MW.
- 3 GeV, 50 Hz, $R=3R_0$, h=6 (or 12) for neutron production.
- Takes the two bunches from ISIS, bucket to bucket matching (very low loss).
- 2 bunches per pulse each of 1.85×10^{13}
- Injector might also be upgraded to 180 MeV for more beam power.
- Ring could also accelerate to 8 GeV at 16.7 Hz.
  - Used for bunch compression (~1 ns) and target tests for a neutrino factory.



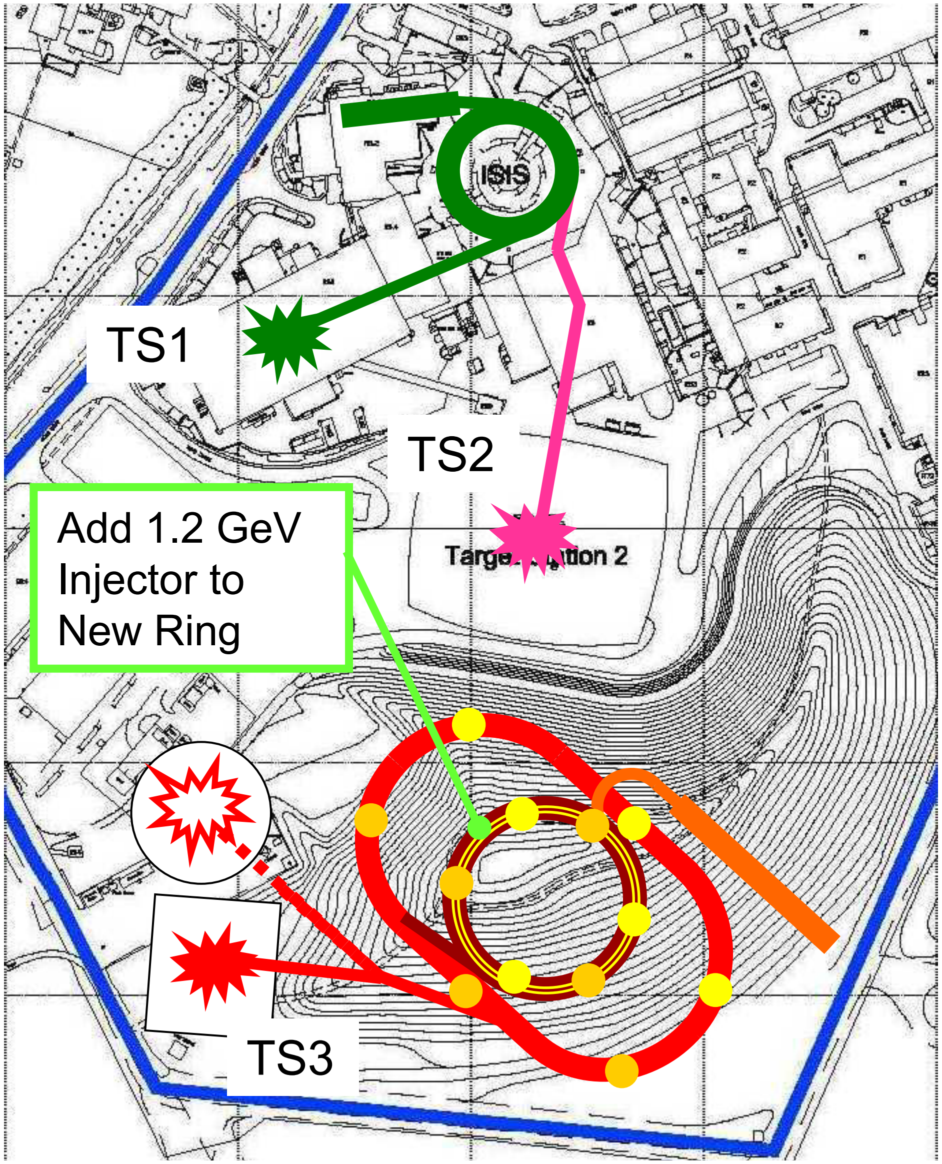
1 MW Upgrade with New Synchrotron II

- Add the 3 GeV synchrotron and build a second 800 MeV synchrotron in the ISIS tunnel
- Build TS3
- 4 bunches per pulse each of 1.85×10^{13} protons at 50 Hz
- ~1.8 MW
- Improved with 180 MeV linac
- Construction difficulties



2.5 MW Upgrade – a new booster system

- Construct a new booster into the 3 GeV synchrotron.
- 180 MeV linac feeding two 50 Hz, h=3, 1.2 GeV synchrotrons with radius 39 m.
- All 6 buckets in the main synchrotron are filled.
- 6 bunches per pulse each of 1.85×10^{13} protons.
- ~2.7 MW at TS3 target.
- A stand-alone system (ISIS2) and ISIS1 could continue to operate as at present.

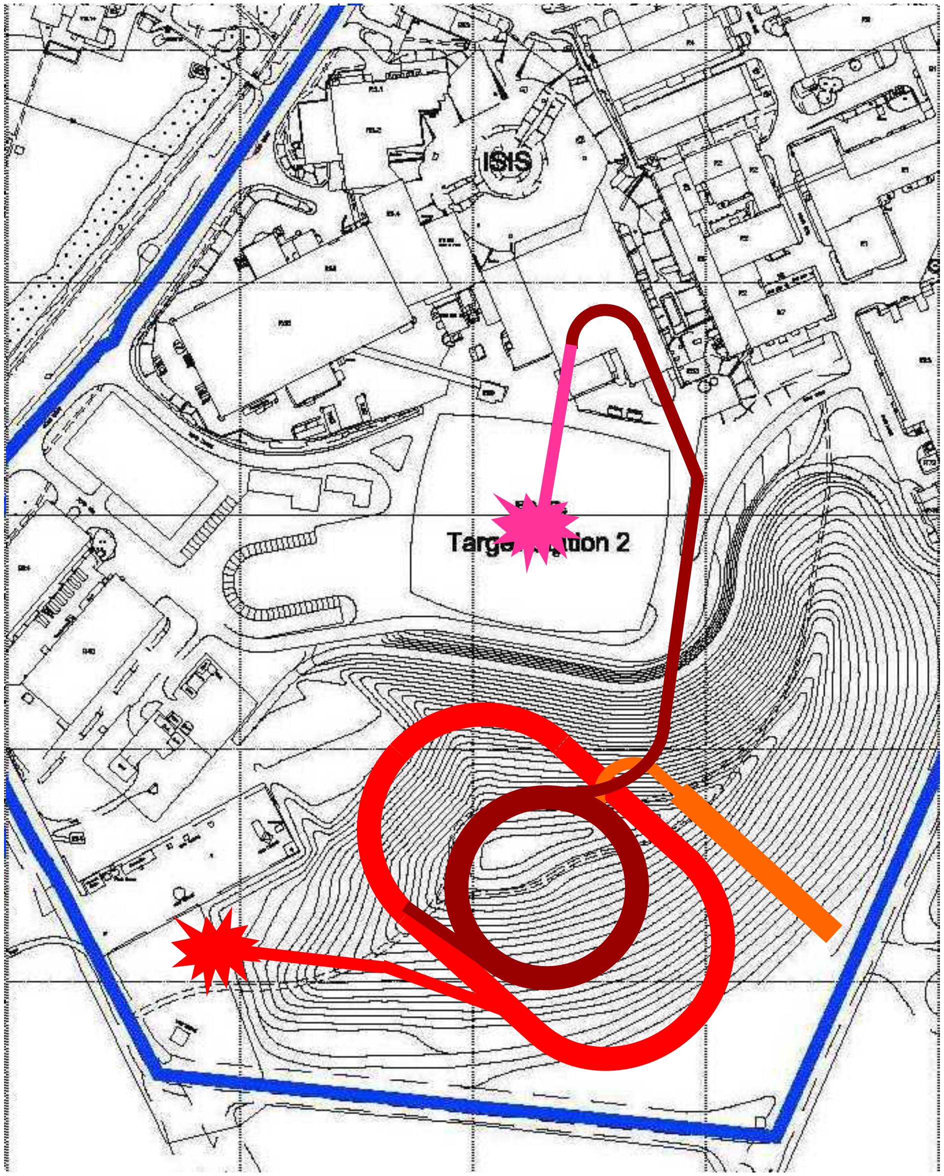


Other Possibilities I

- Low energy (180 MeV) is needed for a neutrino factory (ns bunch length)
- For neutrons, easier to inject at higher energy (less space charge)
- Build a new 800 MeV linac, accumulate in a single booster ring, and accelerate in one 3 GeV synchrotron.
- Either in stand-alone mode with ISIS1 in parallel, or close down ISIS1 entirely.

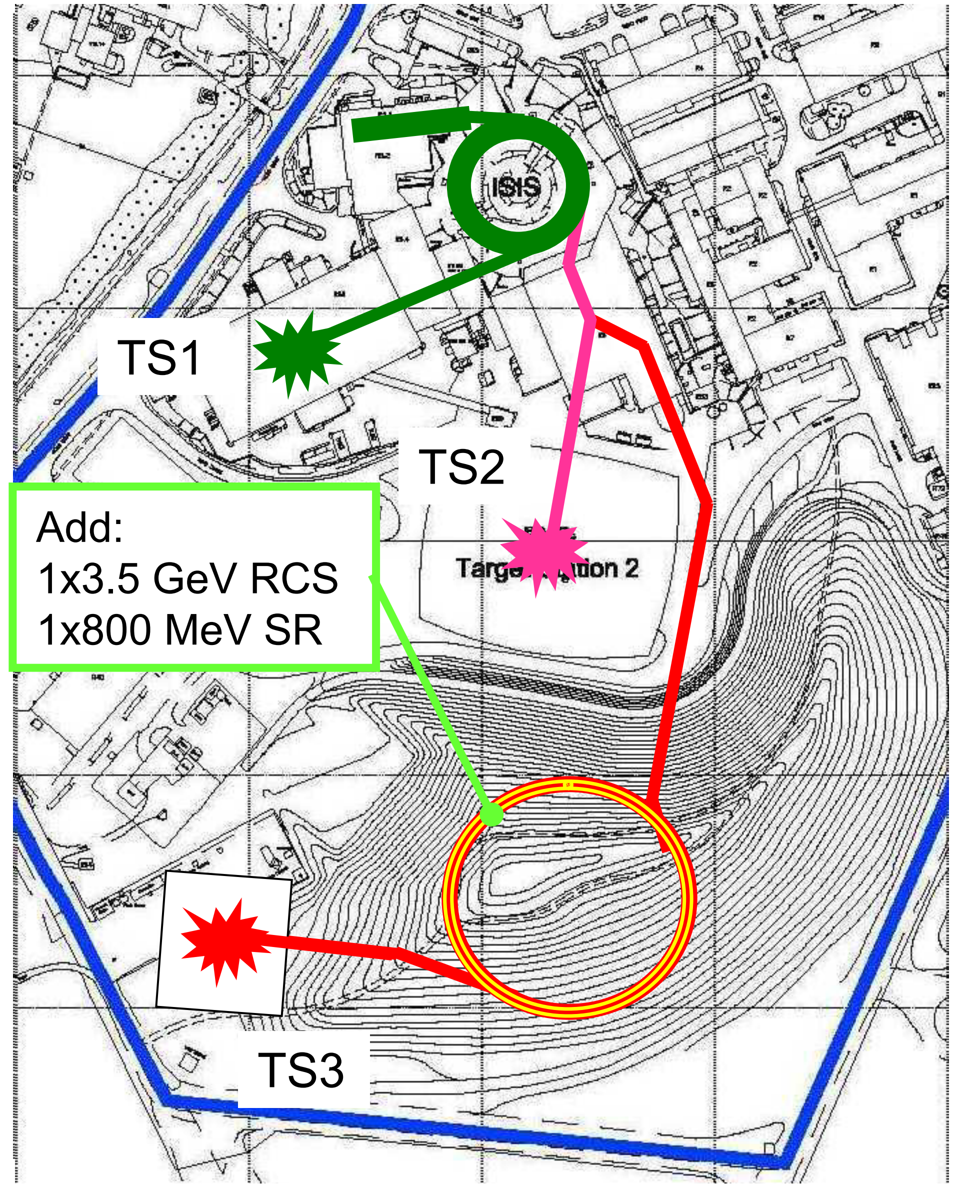
OR:

- Add a second main synchrotron, run both at 25 Hz to 6 GeV
- 6 bunches of $\sim 1.5 \times 10^{13}$ protons in each ring
- Stand-alone ISIS2 ≥ 4 MW



Other Possibilities II – Neutron Optimised Ring

- Take half the beam from ISIS (2 bunches at 25 Hz.)
- Accelerate to 3.5 GeV
- ≥ 0.5 MW on TS3
- 0.12 MW to TS1+TS2.
- For 1 MW:
  - Build 800 MeV storage ring above new RCS
  - Holds 2 bunches for 20 ms
  - Then accelerate 4 bunches to 3.5 GeV in RCS at 25 Hz
  - All pulses go to TS3
- OR storage ring could be a second 3.5 GeV RCS operating on successive half cycles (2 bunches at 50 Hz)
- Could also use 180 MeV linac to ~double number of protons per bunch.



The Future

UK Strategy

- Supporting appropriate investment in the existing facilities
  - ISIS accelerators
  - ISIS target stations
  - ISIS instruments
  - ILL
- Exploring, within an international context and in a timely manner, scientific and technological opportunities for a next generation neutron source for Europe.
- The UK has the potential to build a megawatt-class spallation neutron source through the upgrade of ISIS, but will defer further planning for this option until the outcome of the wider discussions on European plans is known