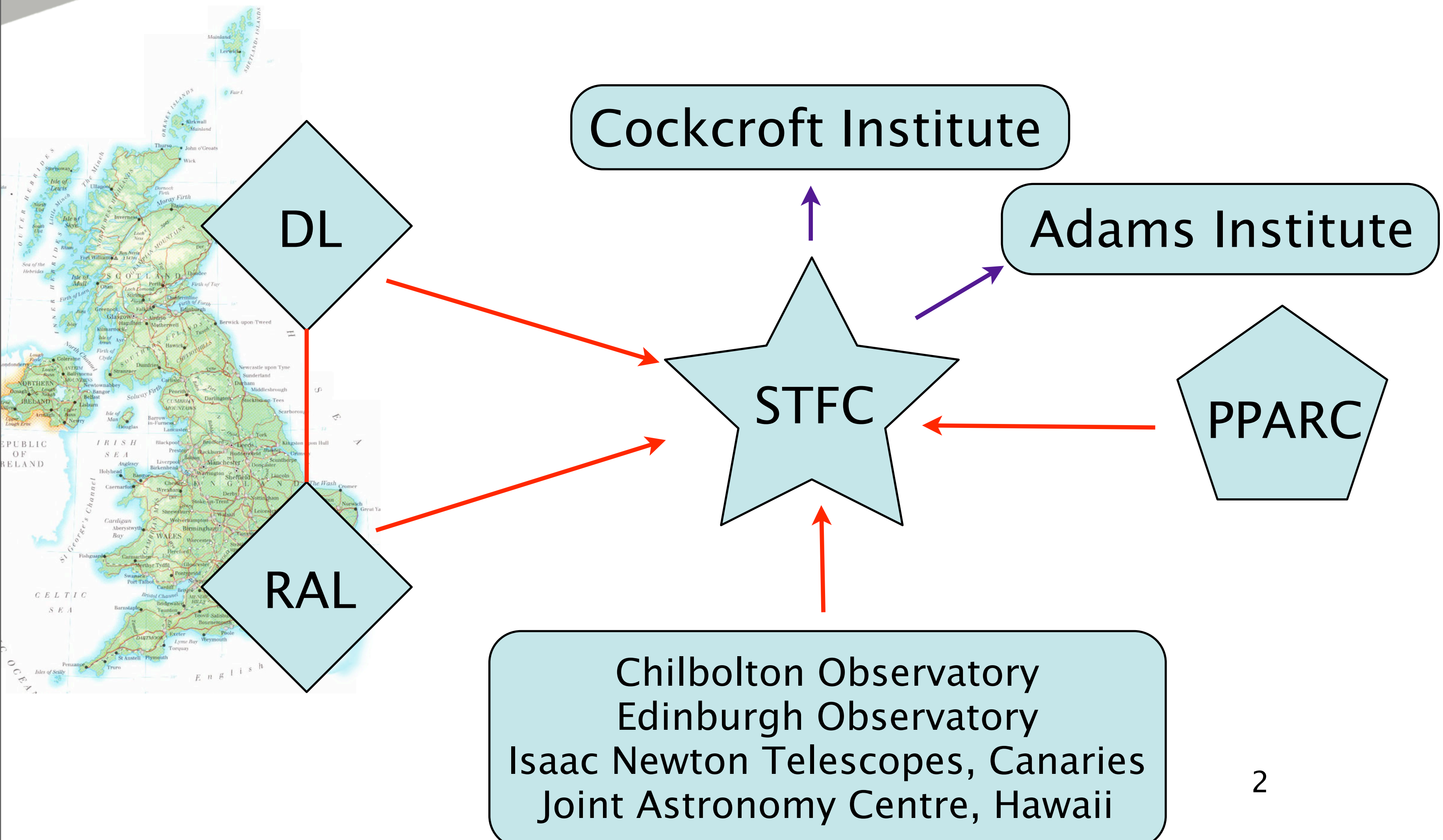
Science & Technology Facilities Council
ASTeC

Studies of High Power Proton Drivers in the U.K.

Chris Prior

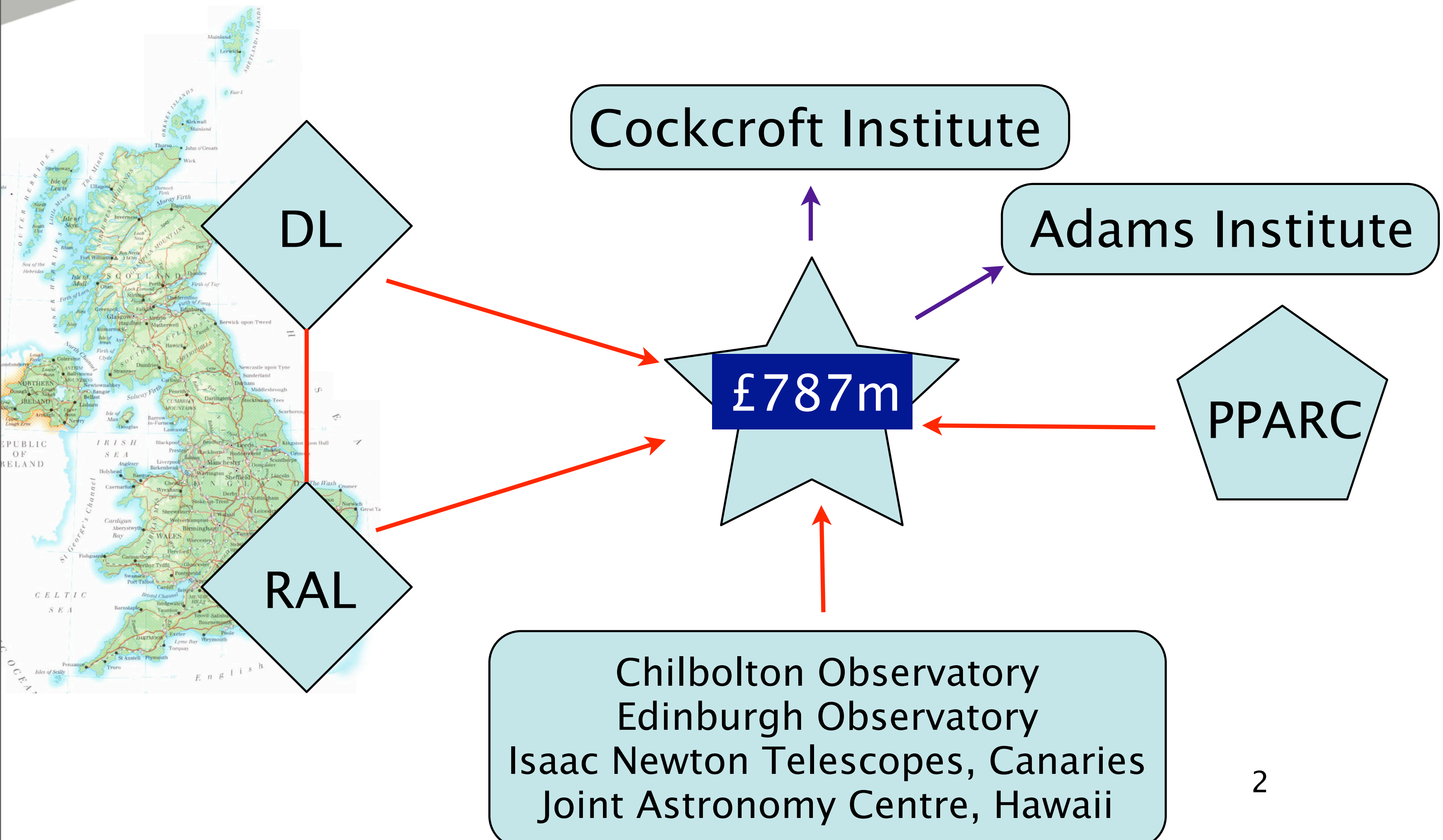
ASTeC Intense Beams Group
Rutherford Appleton Laboratory

UK Accelerator Centres



Science & Technology Facilities Council
ASTeC

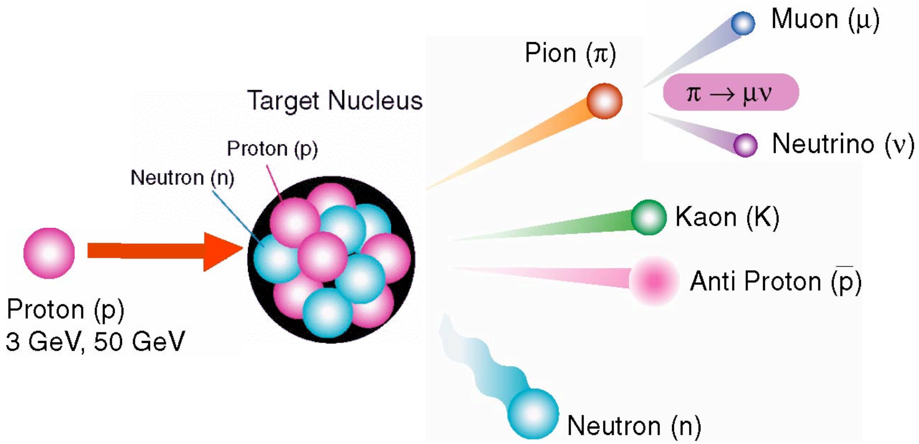
UK Accelerator Centres



Science & Technology Facilities Council
ASTeC

Proton Driver

- RAL work is directed at a high intensity proton accelerator delivering several MW of average beam power to a production target
- Applications to
  - spallation neutron sources
  - nuclear waste transmutation
  - energy amplifier
  - secondary particle production
  - neutrino superbeams
  - neutrino factories
- For a Neutrino Factory:
  - 4 MW at ~50 Hz, ~10 GeV
  - bunches of ~1 ns rms duration.
- For a Neutron Source
  - 4-5 MW at ~50 Hz, 1-3 GeV
  - bunches of $\sim 1\ \mu s$
- Note: the ISIS spallation neutron source operates at ~160 kW.



Materials & Life Sciences at ~3 GeV

Nuclear & Particle Physics at ~50 GeV

R&D for ADS at ~0.5 GeV

Science & Technology Facilities Council
ASTeC

Main Design Issues

- Choice between
  - Full energy linac and accumulator/storage rings (e.g. SNS, ESS)
  - Low/intermediate energy linac, booster RCS, main accelerating ring (synchrotron or FFAG) (e.g. J-PARC)
- Requirement for very low uncontrolled beam loss throughout machine.
  - met with fast beam chopper in linac, achromats and advanced collimation systems
- Beam accumulation via charge exchange injection $H^- \rightarrow H^+$
- Trapping and acceleration in rings (instability studies, halo, emittance growth)
- Nanosecond bunch compression for Neutrino Factory
  - imposes additional considerations beyond a neutron source.

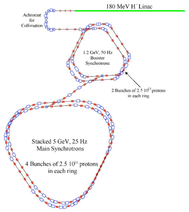
Science & Technology Facilities Council
ASTeC

Possible Schemes

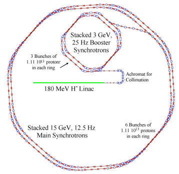
- H^- linac with pairs of 50 Hz booster and 25 Hz driver synchrotrons (RCS)
- H^- linac with 50 Hz booster RCS and 50 Hz non-scaling FFAG
- H^- linac with chain of 3 FFAGs in series
- H^- linac with 2 slower cycling synchrotrons and 2 holding rings
- Full energy H^- linac with accumulator and compressor rings - CERN, Fermilab

UKNF Proton Drivers

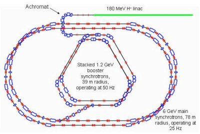
- 5 GeV, 50 Hz: two-ring booster (50Hz) feeding two main synchrotrons (25 Hz)



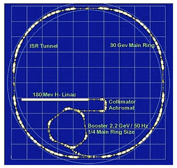
- 15 GeV, 25 Hz: two-ring boosters (25 Hz) feeding two main synchrotrons (12.5 Hz)



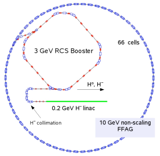
- 6-8 GeV, 50 Hz design: as above, suggested as a development path for ISIS



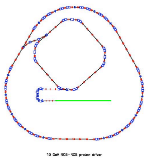
- 30 GeV, 8.33 Hz, slow cycling synchrotron, intended as upgrade for CERN PS



- 10 GeV, 50 Hz: 3 GeV booster feeding single FFAG

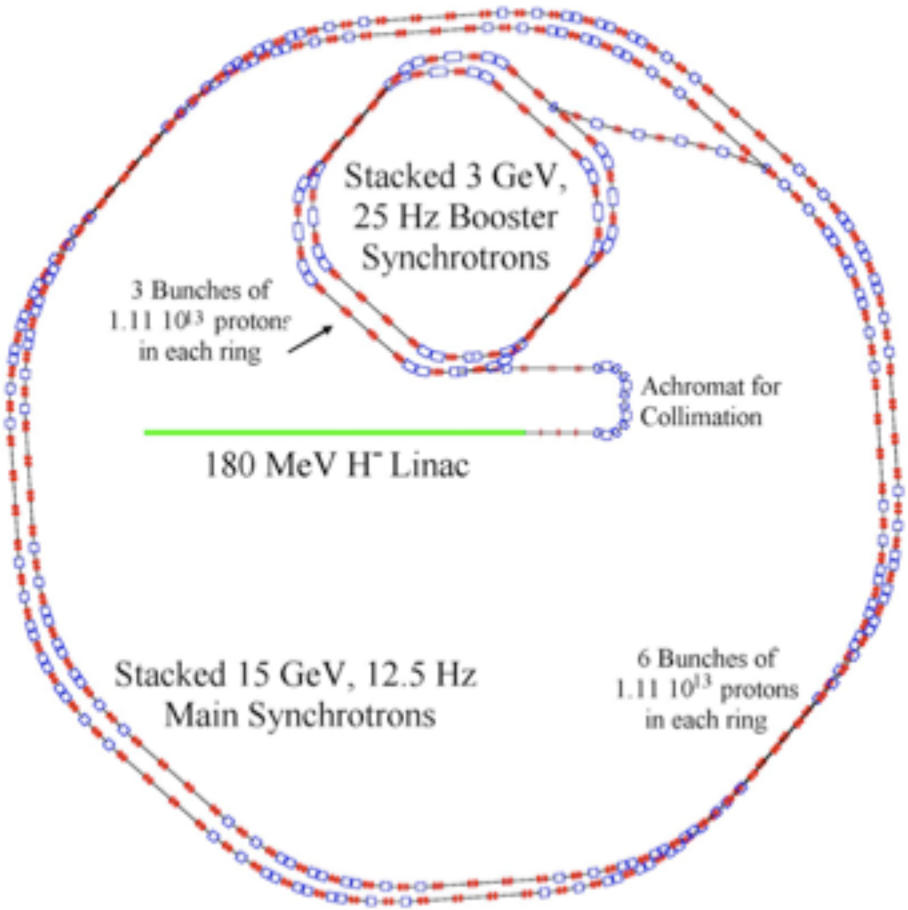


- 10 GeV, 50 Hz: 3 GeV booster feeding single RCS



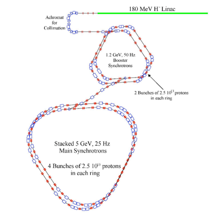
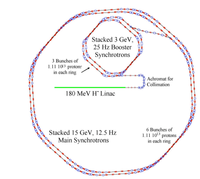
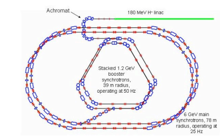
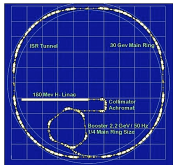
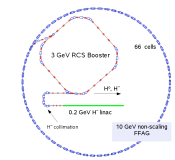
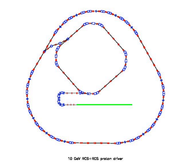
UKNF Proton Drivers

- 5 GeV, 50 H synchrotron
- 15 GeV, 25 synchrotron
- 6-8 GeV, 50 for ISIS
- 30 GeV, 8.3 CERN PS
- 10 GeV, 50
- 10 GeV, 50



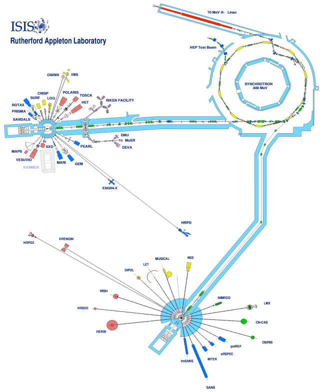
ent path

rade for

Recent Developments at ISIS

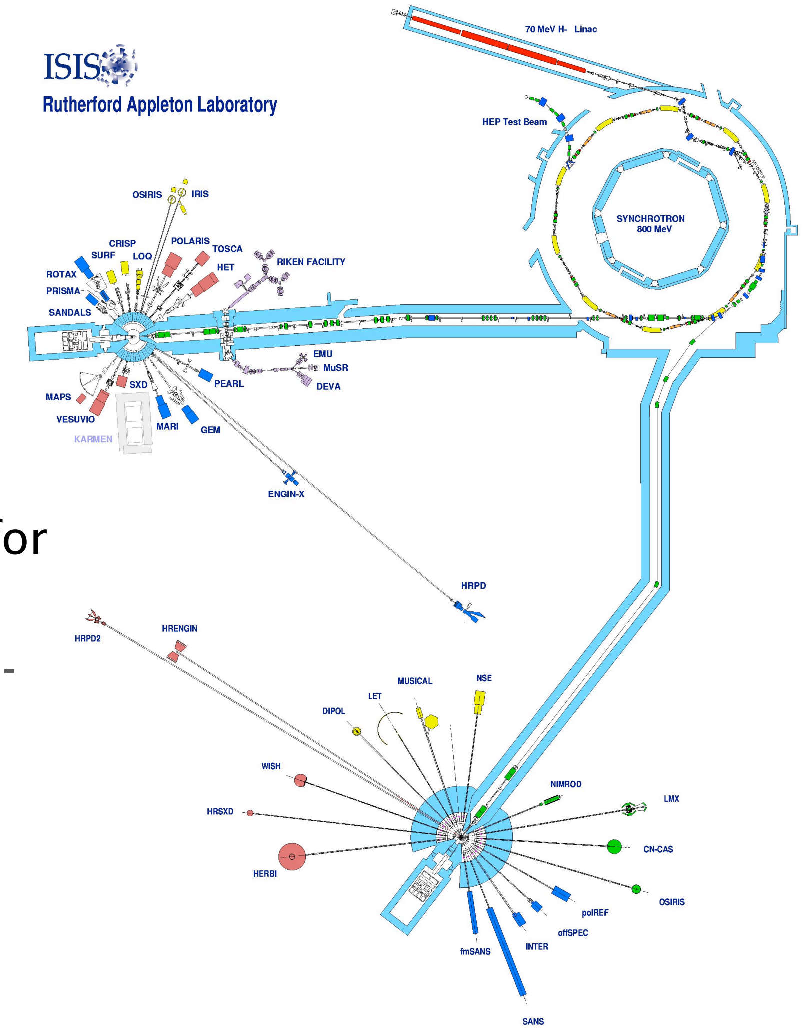
- 70.44 MeV H^- linac
- Charge exchange injection into 800 MeV RCS
- 50 Hz operation
- 200 μA, 160 kW
- Dual harmonic system to upgrade to ~240 kW
- Otherwise intensity limited by space charge



Science & Technology Facilities Council
ASTeC

ISIS Spallation Neutron Source

- Recent accelerator developments
  - injector upgrade
  - dual harmonic RF system
- New 10 Hz target station, TS2
  - takes one pulse in five from ISIS synchrotron
  - 48 kW power, 60 μA current
  - optimised for cold neutron production for research into
    - Soft Matter, Advanced Materials, Bio-materials, Nano-technology
- ISIS upgrade studies
  - linac development (incl. HIPPI)
  - MW proton driver for neutrons or neutrinos

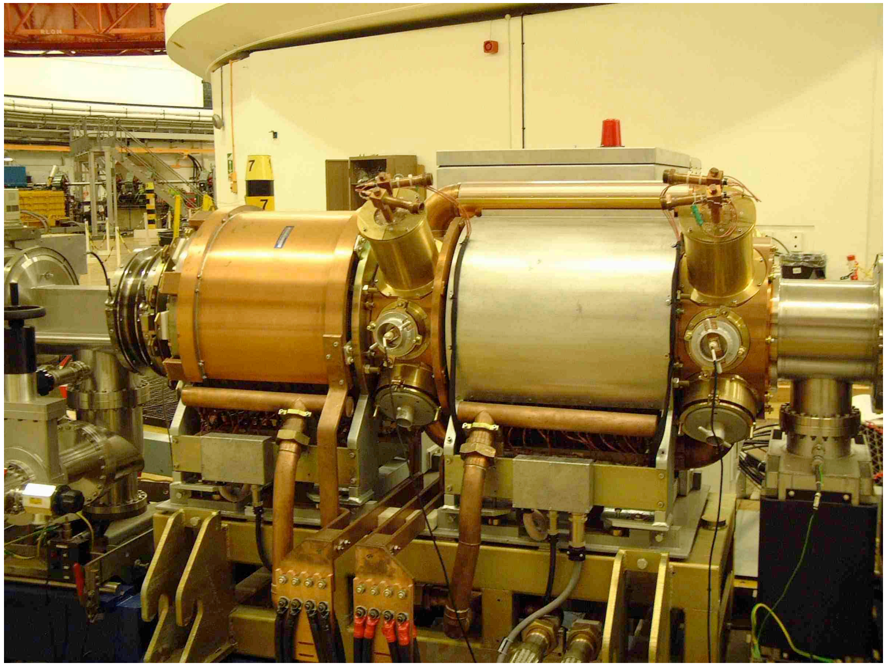


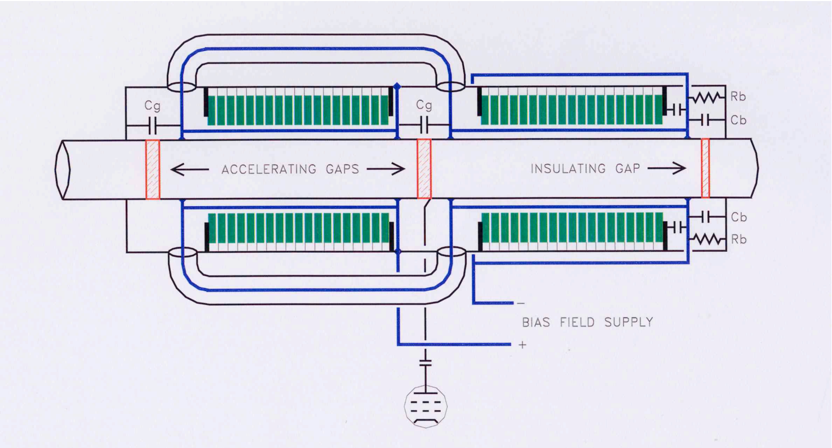
Dual Harmonic RF Accelerating System

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

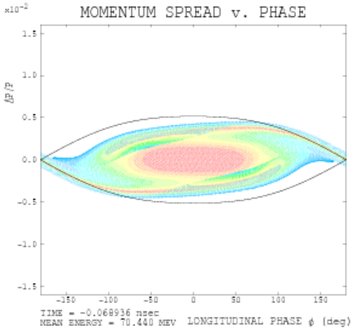
$$V(\phi, t) = \hat{V}(t)\Big[\sin\phi - \delta\sin(2\phi + \theta)\Big]$$

- 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.

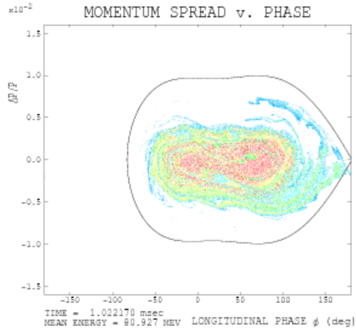




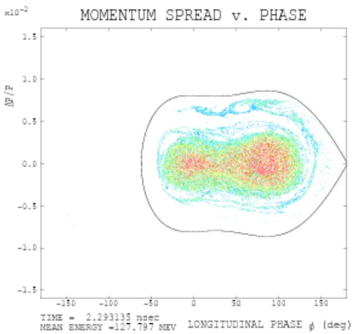
Dual Harmonic RF: Simulation of 3 ×10^{13} ppp



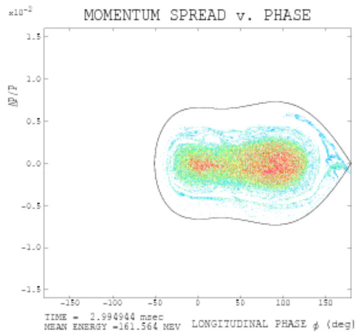
End of Injection, 70 MeV



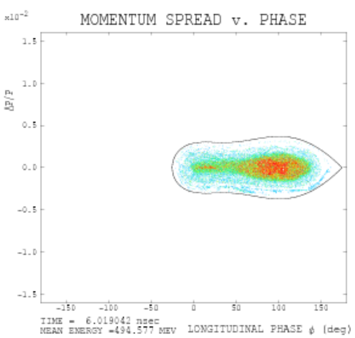
1 msec, 80 MeV



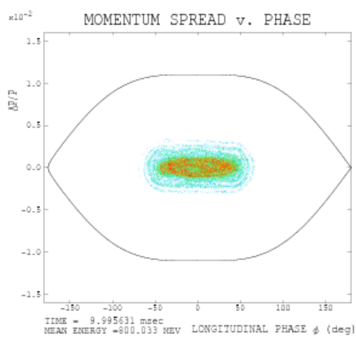
2.5 msec, 140 MeV



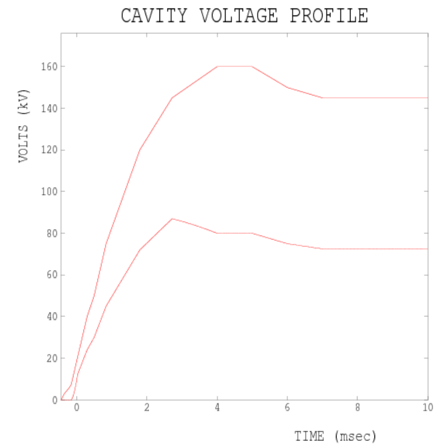
3 msec, 180 MeV

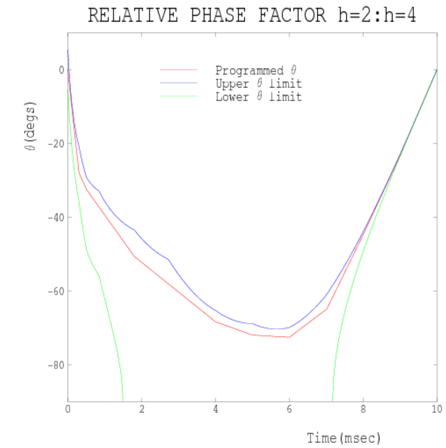


6 msec, 500 MeV



10 msec, 800 MeV



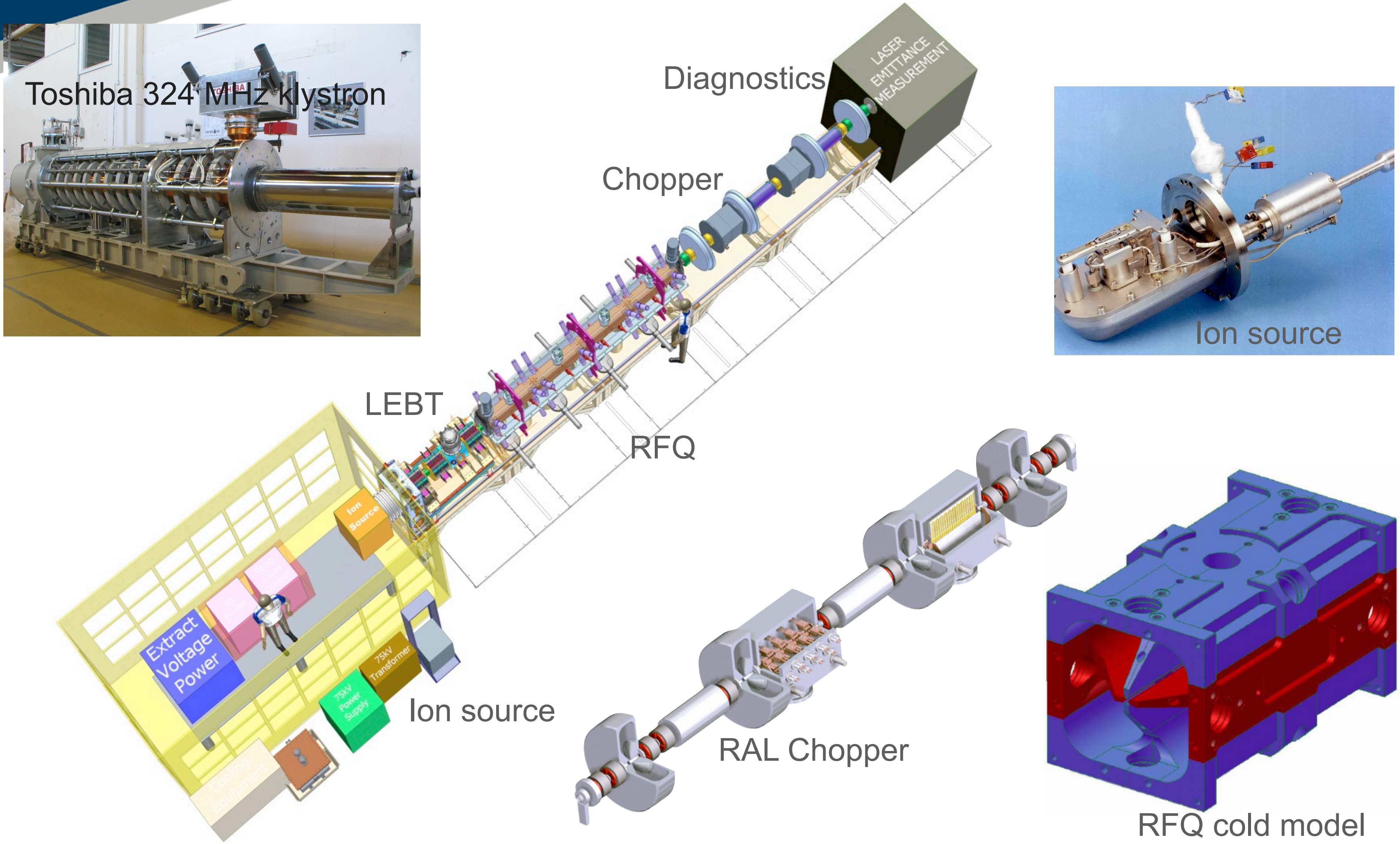


Reduced beam loss during injection and trapping; some very small loss (<0.1%) at about 3-4 ms (~200 MeV). Agrees with simulations

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

160 kW → 240 kW

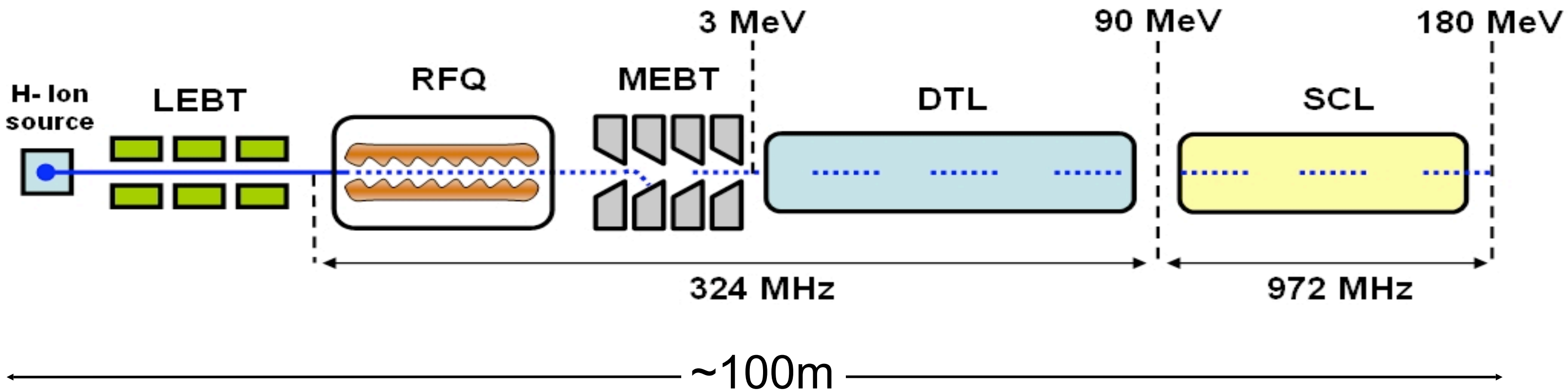
Linac Front-End (FETS)



RAL Chopper
RFQ cold model

High Current 180 MeV H⁻ Linac Studies

- An H^- linac to ~200 MeV is common to all RAL proton accelerator designs, whether for neutron sources or as the driver for a muon-based neutrino factory.
- RAL's work related to similar studies at CERN for Linac4



Plans for £20m Proton Driver test facility at RAL. Could be linac accelerating structures or a test model of a proton FFAG

Science & Technology Facilities Council
ASTeC

Science & Technology Facilities Council
ASTeC

ISIS MW Upgrades

Option		Comments	Beam Power (MW)	Neutron Yield
1(a)	Add 180 MeV Linac	Technical Issues	~ 0.4	1.7
1(b)	Add 800 MeV RCS	Operational Issues	~ 0.5	2.0
1(c)	Upgrades 1(a) + 1(b)	Technical/Operational Issues	~ 0.9	3.8
2	Add ~ 3 GeV RCS	Recommended 1st Upgrade	1	3.2
3	Add ~ 6 GeV RCS	Technical/Cost Issues	2	5.6
4	Upgrades 1+2 or 1+3	Technical/Operational Issues	~ 2 – 6	~ 6.4 – 16.8
5	400 – 800 MeV Linac + 3 GeV RCS	Recommended 2nd Upgrade	2 – 5	6.4 – 16.0
6	1.334 GeV Linac + Accumulator Ring	Good "Green Field" Option	5	18.8

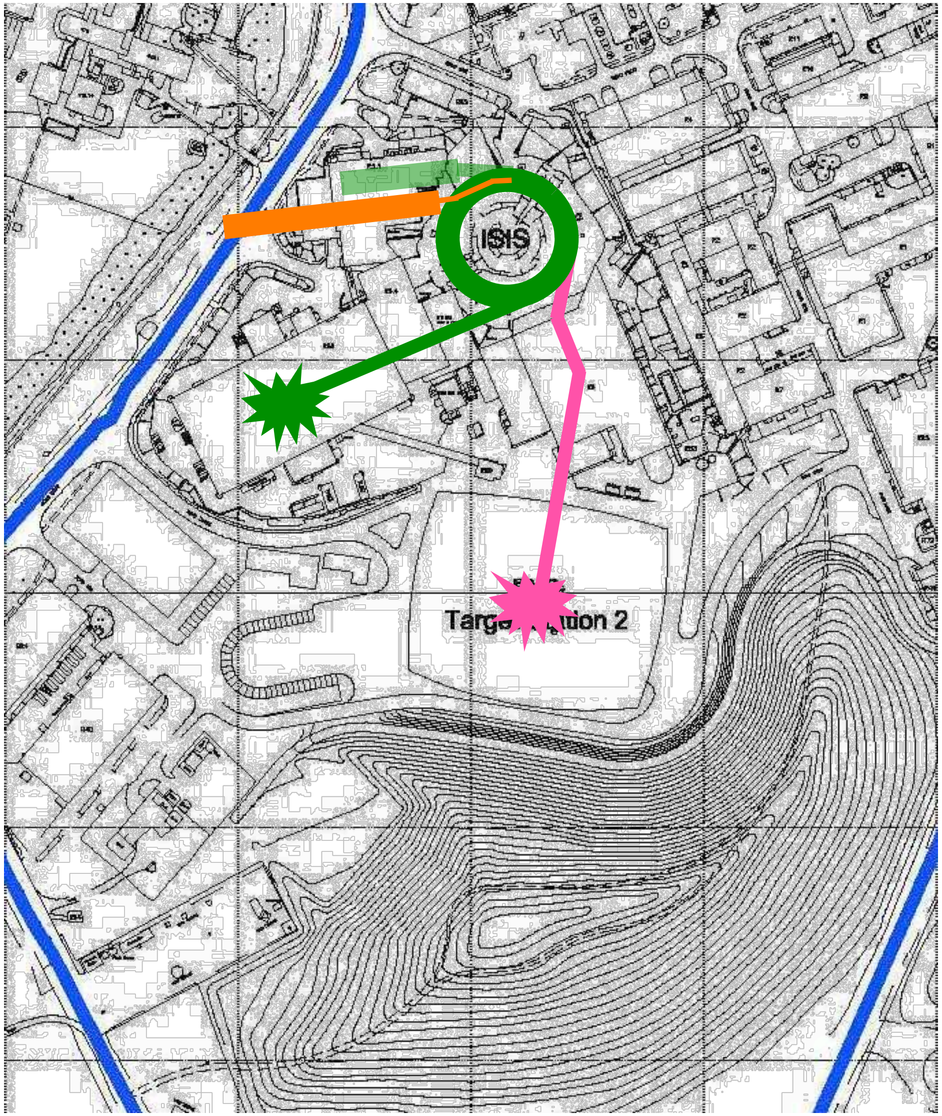
- designs optimised for neutron production
- all include beam to TS2
- primary considerations are:
  - cost relative to new facility
  - impact on ISIS operations

Expedient Upgrade

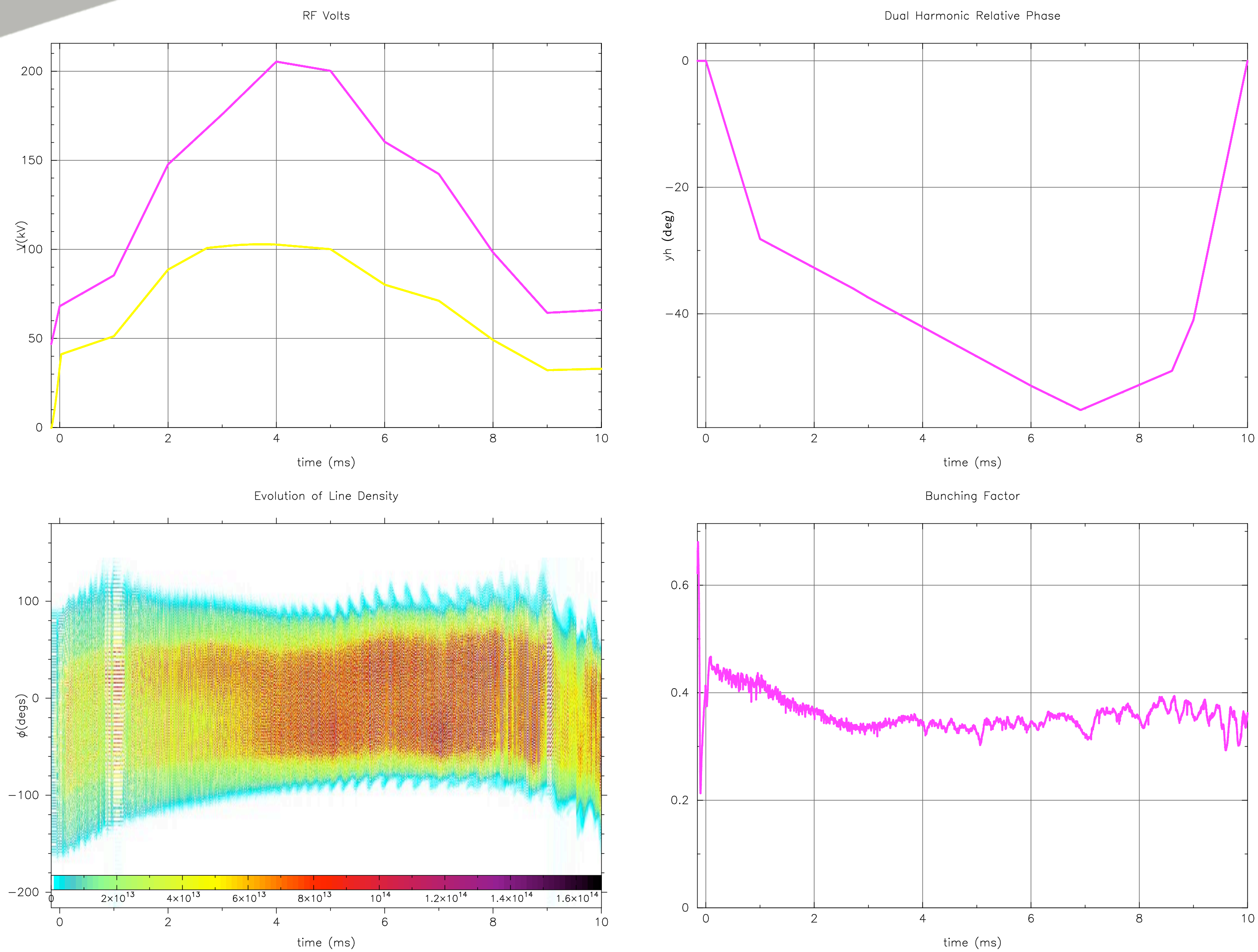
In present financial climate, "cheap" option to safeguard future of ISIS:

- Replace existing 70MeV linac with new injector.
- Lower the space-charge, more accumulated beam.
- Same injection geometry, some upgrades to ring (RF).
- Increase rep. 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.



Injection into ISIS at 180 MeV



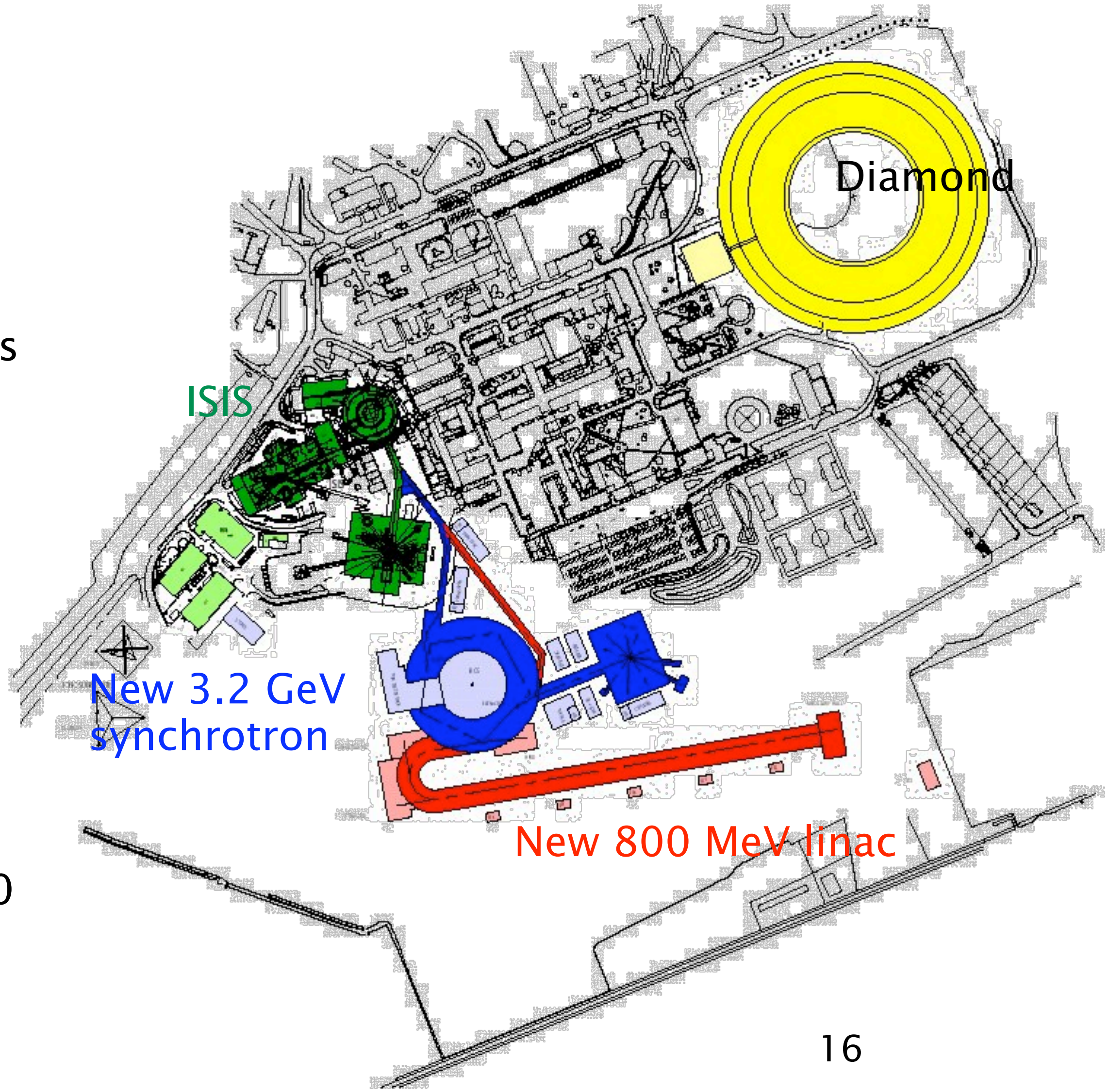
- Dual harmonic RF system
- 0.5 MW beam
- Good bunching factor
- 0.05% simulated beam loss
- 200 ns final bunch length

Science & Technology Facilities Council
ASTeC

Favoured Option for Upgrading ISIS

I. Add new 3.2 GeV synchrotron
   - Bucket-bucket transfer (2 bunches) from ISIS
   - Simple energy increase gives ~0.75 MW to new neutron production target (40 Hz)

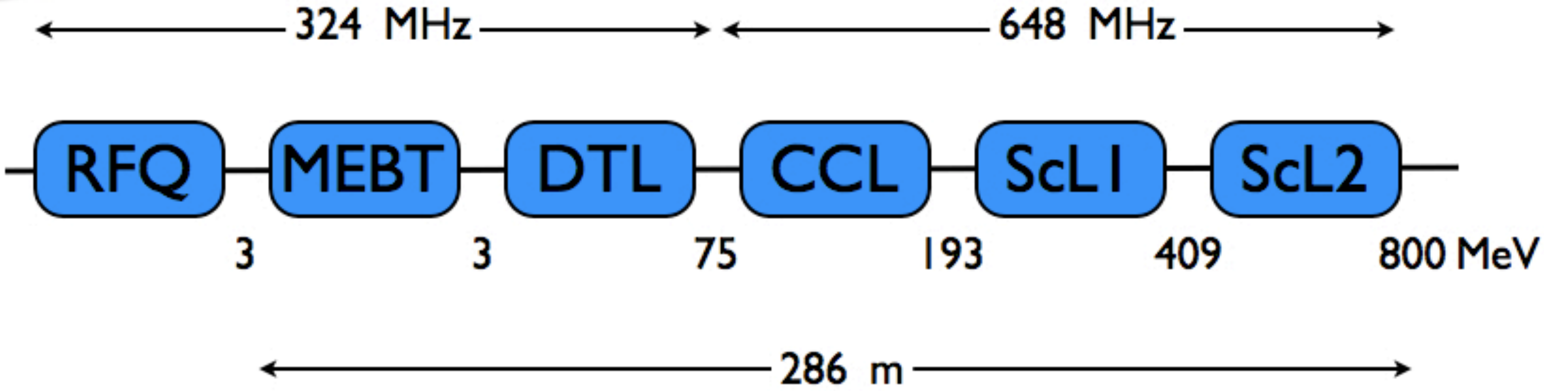
II. Build new 800 MeV H^- linac; possibly decommission ISIS
   - Charge exchange injection, phase space painting
   - 5 bunches for neutron production
   - 2 MW at 30 Hz, ~5 MW at 50 Hz

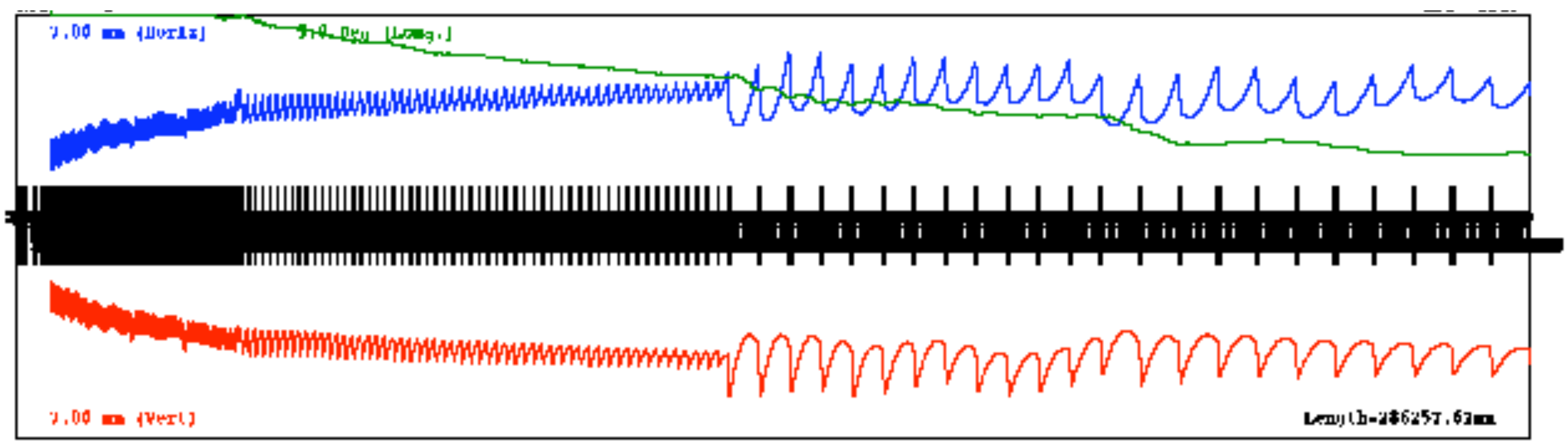


H^- linac design parameters

Beam power for 2 MW, 30 Hz, 3.2 GeV RCS:	0.5 MW
Beam pulse current before MEBT chopping:	43.0 mA
Beam pulse current after MEBT chopping:	30.0 mA
Number of injected turns for a 370 m RCS:	~500 turns
Beam pulse duration at the 30 Hz rep rate:	~700.0 μs
Duty cycle for the extent of the beam pulse:	~2.1 %
MEBT(in) normalised rms emittances (π mm mr):	0.25, 0.375
MEBT(out) normalised rms emittances (π mm mr):	0.292, 0.41
Cell equipartition trans/long phase shift ratios:	1.40

Initial Linac Outline Design

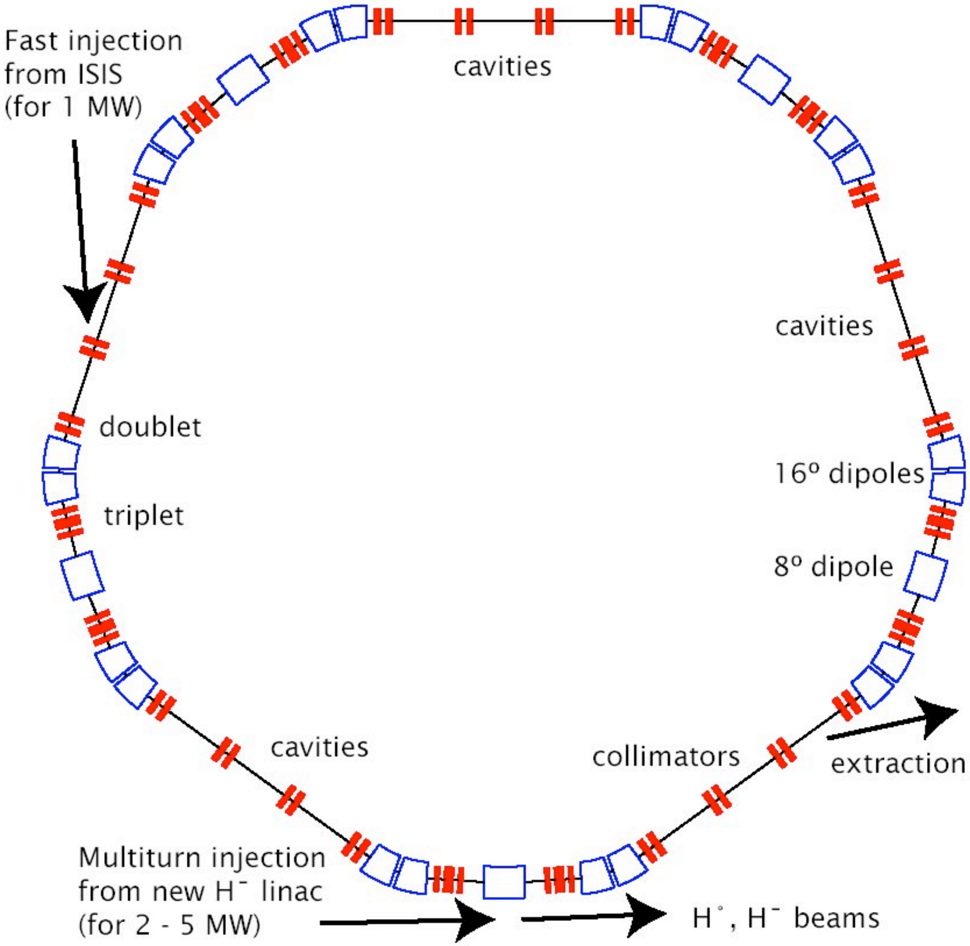




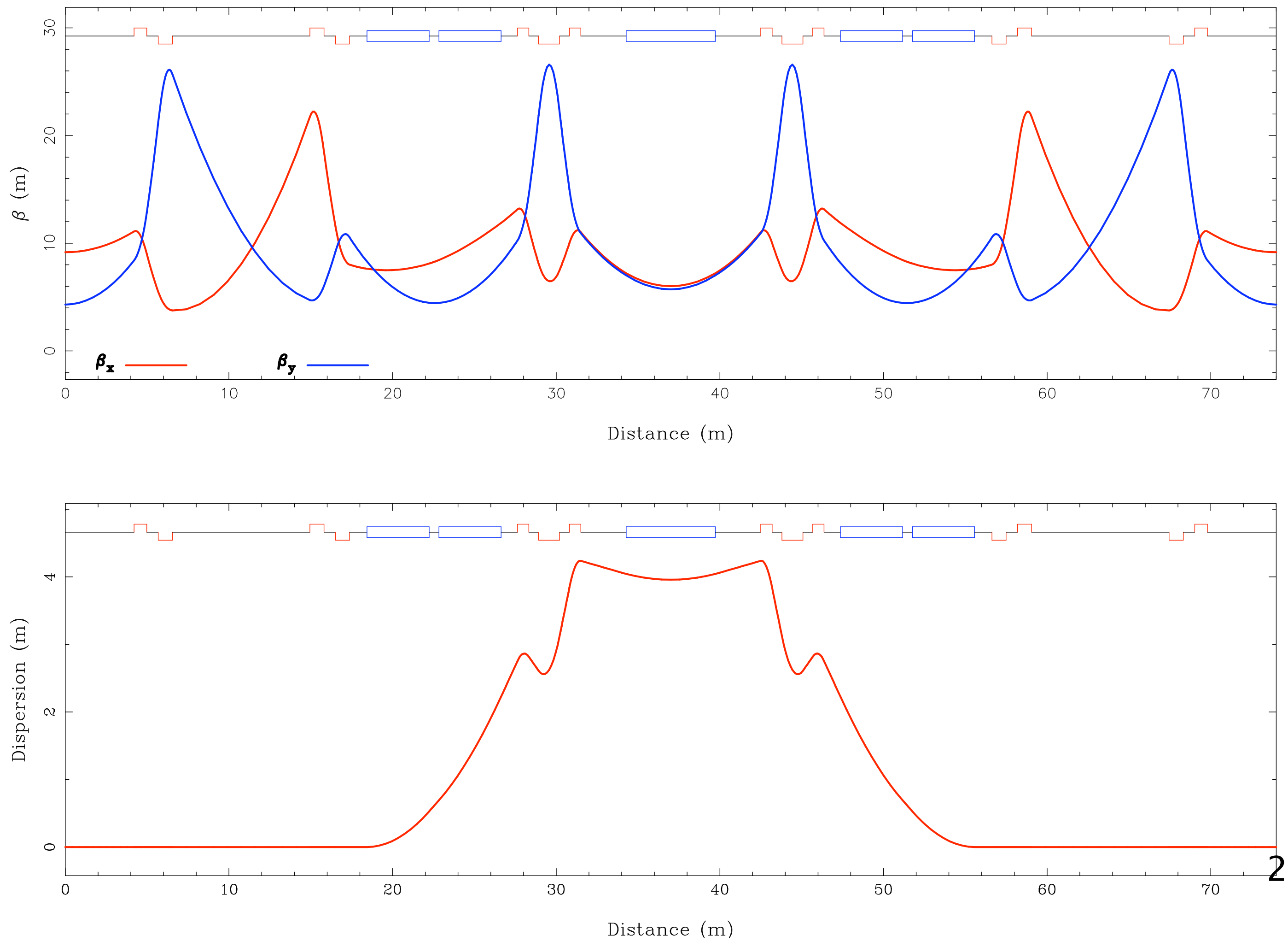
Science & Technology Facilities Council
ASTeC

3.2 GeV Rapid Cycling Synchrotron

Energy	0.8 – 3.2 GeV
Rep Rate	50 Hz
C, R/R_0	367.6 m, 9/4
Gamma-T	7.2
Q_h, Q_v	7.21, 5.73
h	9
f_{rf} sweep	6.1-7.1 MHz
Peak V_{rf}	~ 750 kV
Peak K_{sc}	~ 0.1
ε_l per bunch	~ 1.5 eV s
$B[t]$	sinusoidal



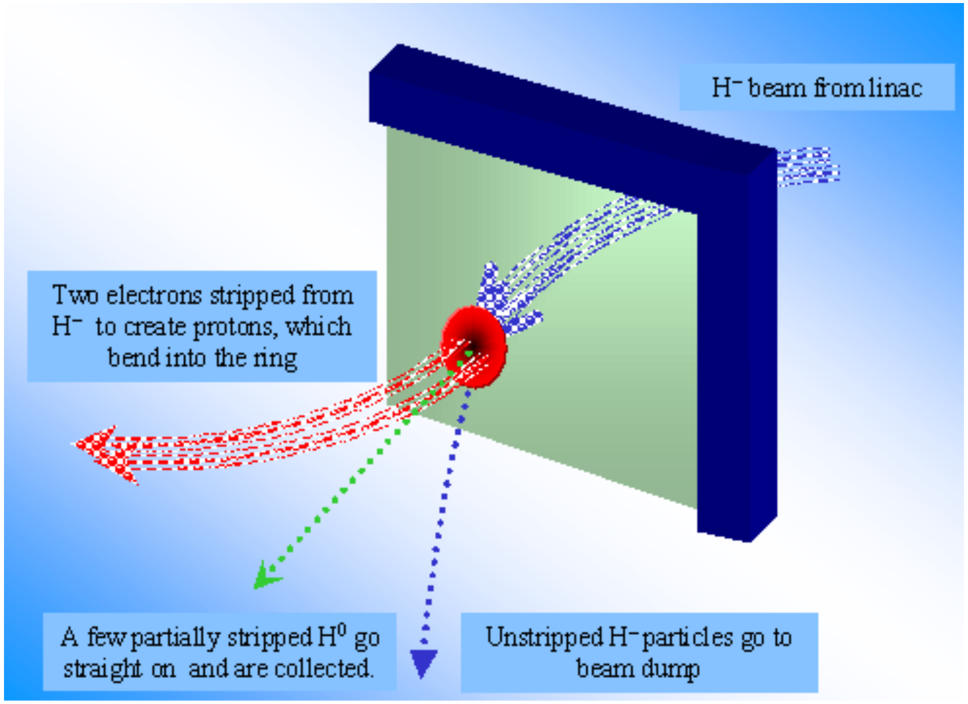
Beta Functions and Dispersion



Injection

- Charge exchange injection foil, laser stripping

  Foil issues:
  - Stripping efficiencies
  - Multiple Coulomb scattering
  - Large angle and Nuclear scattering
  - Energy straggling
  - Heating
  - Stress and buckling
  - Lifetime
  - Radiation
  - Stripped Electrons
  - Emittance Growth
- Painting
  - Transverse and longitudinal coupling
  - options for transverse painting
  - options for longitudinal painting
- Unstripped Beam (H^0, H^-)

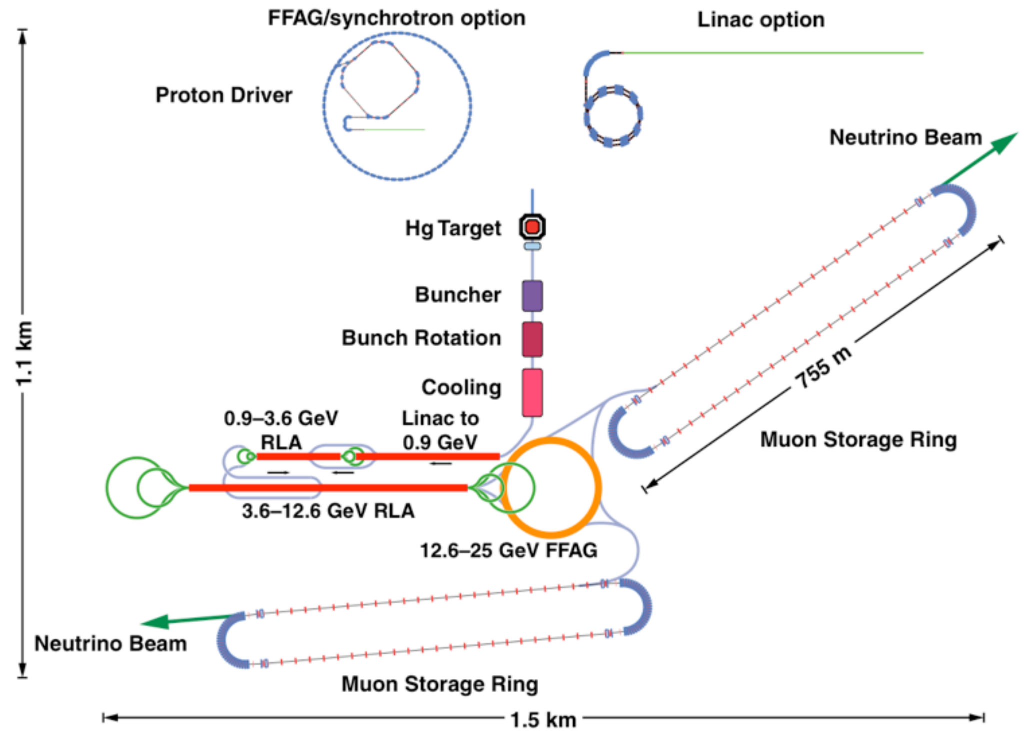


Neutrino Factory

- Proton driver
  - Primary beam on production target
- Target, capture channel
  - Create π, decay to μ
- Cooling
  - Reduce transverse emittance
- Muon acceleration
  - ~130 MeV to 20-50 GeV
- Decay ring(s)

  Store for ~500 turns

  Long production straights

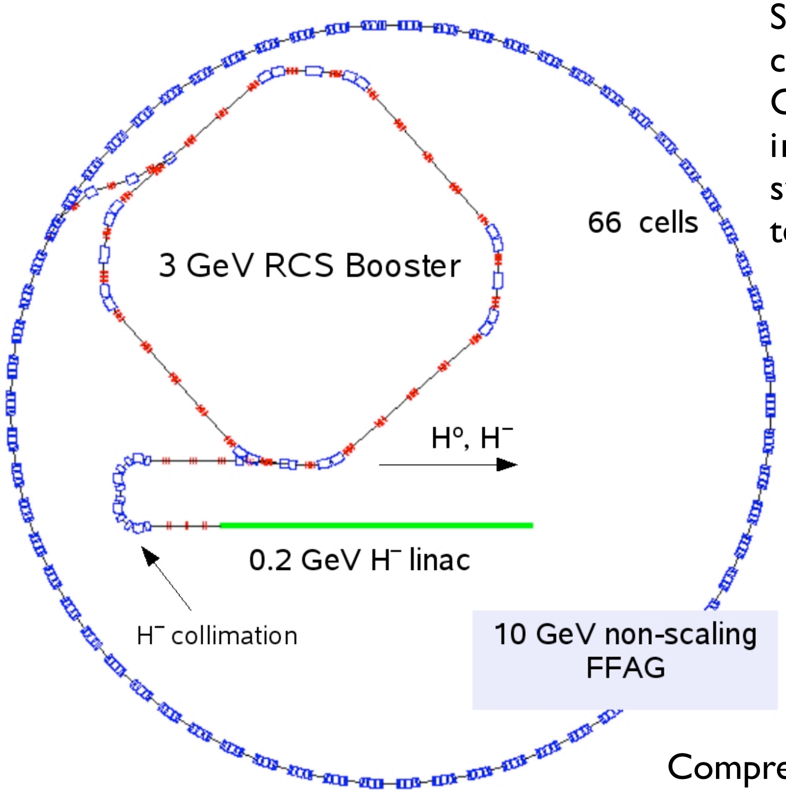


Proton Driver for a Neutrino Factory

Lower injection energies provide smaller bucket area in the ring and the small longitudinal emittance needed for final ns bunch compression. Studies show that 180 MeV is a realistic energy for NF.

Special achromat for collimation (longitudinal and transverse) and momentum ramping for injection

Separate booster ring designed for low loss phase space painting for beam injection and accumulation.
Synchrotron moving buckets give flexibility to capture all of the injected beam.



Separate main ring with optics chosen for ns bunch compression. Could be FFAG (cheaper but insufficiently developed) or a synchrotron (reliable, tried and tested)

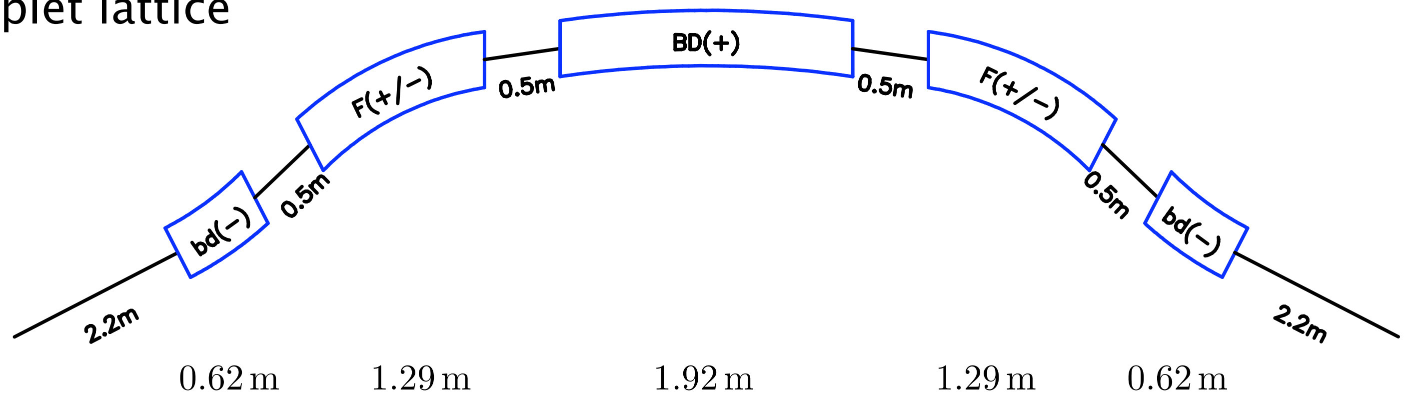
Compressed bunches need to be held and sent to target at intervals of 20-100 μs. Possible in FFAG and also synchrotron with flat top.

RAL FFAG Driver

- Advantages of non-scaling FFAG
  - high duty cycle, lower RF fields.
  - metallic vacuum chambers (v. ceramic for RCS).
  - single rings and transfer lines (v. double for RCS systems) => cheaper.
  - adiabatic bunch compression easier (v. LAR system).
  - bunches can be held in compressed state until needed.

RAL Proton FFAG

- Pumplet lattice

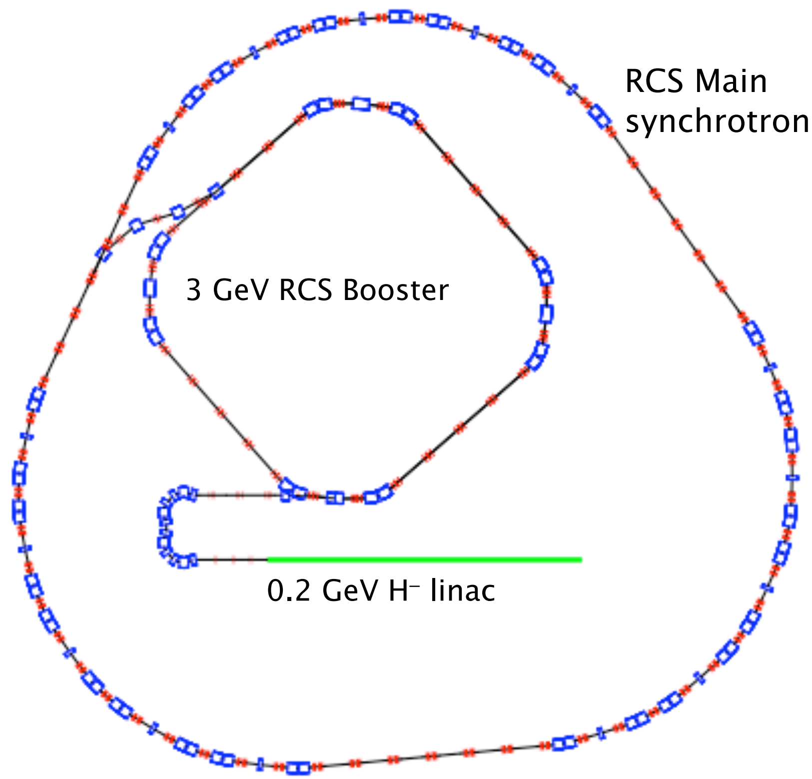


- 3.2-10 GeV, non-isochronous, non-linear, non-scaling
- 66 cells, long straights for injection and extraction.
- $\nu_h = \frac{4}{13},\ \nu_v = \frac{3}{13}$ for zero chromaticity at all energies.
- Non-linear betatron excitations and structure resonance effects are reduced.
- Large dynamic aperture.
- γ_t varies with energy (imaginary -> real -> decreases to 21.86 at 10 GeV).
- Bunch compression requires 1.30 MV per turn for 3.0 ns rms bunches.

Science & Technology Facilities Council
ASTeC

10 GeV Synchrotron Proton Driver (IDS)

- High intensity ~10^{14} protons
  - Achieved with phase space painting in RCS booster
- 50 Hz rep rate
- Booster circumference 400 m
- Bunch area (h=3) 1.1 eV.sec
- ns bunch compression
  - Achieved with RCS accelerator (h=24)
  - 1.26 MV per turn for 3 ns rms compression
  - RCS circumference same as for FFAG (~800 m)
- Finemet, rather than ferrite, used for rf cavities.

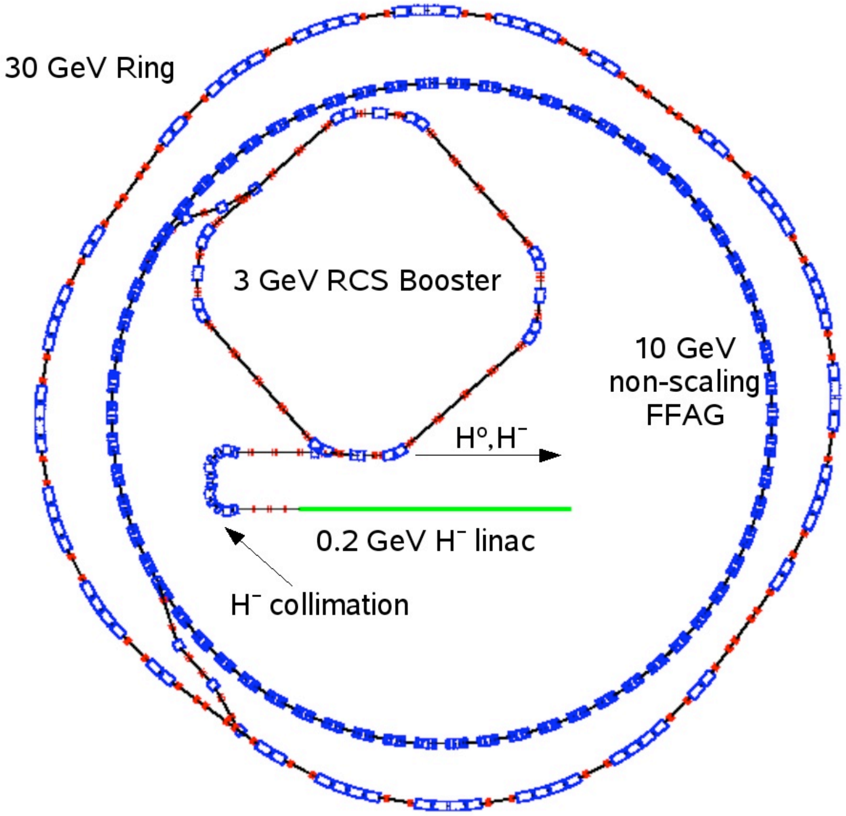


Extending NF driver to Muon Collider

	Neutrino Factory	Muon Collider
Beam power (MW)	4	4
Number of bunches	3	1
Bunch duration (rms ns)	3	3
Bunch area (eV.s)	1.1	3.3
Repetition rate (Hz)	50	50/4 or $\boxed{50/3}$
Kinetic energy (GeV)	10	40 or $\boxed{30}$
Circumference (m)	800	1300 or $\boxed{950}$
Protons per bunch (10^{13})	1.67	6.67 or $\boxed{5.0}$

Idea is to add a further ring to 10 GeV NF driver (adapted)

30 GeV Proton Driver for a Muon Collider



- 10 GeV NF driver modified
  - Single bunch
  - Rep rate 50/3=16.7 Hz
  - Bunch area x3
  - RCS h=3 to h=1
  - FFAG h=24 to h=8
  - RF reduced by factor 3
- 30 GeV RCS
  - Circumference 952 m
  - Peak voltage per turn for compression 1.4 MV
  - Compressed bunch 2.5 ns

Can Upgraded ISIS be used for NF?

Fundamental criterion: must not affect neutron production to users

Upgraded ISIS	5 bunches	30 Hz	3.2 GeV	2 MW
Increase rep. rate	5 bunches	50 Hz	3.2 GeV	2 x 5/3 MW
Neutron use	3 bunches	50 Hz	3.2 GeV	2 MW
NF use	2 bunches	50 Hz	10 GeV	4.2 MW

Increase repetition rate to 50 Hz, leave 3 of the 5 bunches for neutron use, put remaining two into a separate new synchrotron and accelerate to 10 GeV. Leaves neutron production unaffected and gives 4 MW for NF

BUT:

Proton bunches for neutron production have large longitudinal emittances.

Can we do required ns bunch compression with a neutron optimised beam?

Note: J-PARC, with neutron production at 3 GeV, can compress only to 10 ns rms in the 50 GeV ring

Science & Technology Facilities Council
ASTeC

Outstanding Issues

- Neutron Sources
  - high intensity issues (space charge, instabilities, electron cloud)
  - H^- laser stripping injection
  - multi-megawatt targets
- Neutrino Factory
  - target capability and development (MERIT 2007)
  - bunch compression (BNL studies 1999)
  - proton FFAG development