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Liouvillean Injection for ESSnuSB

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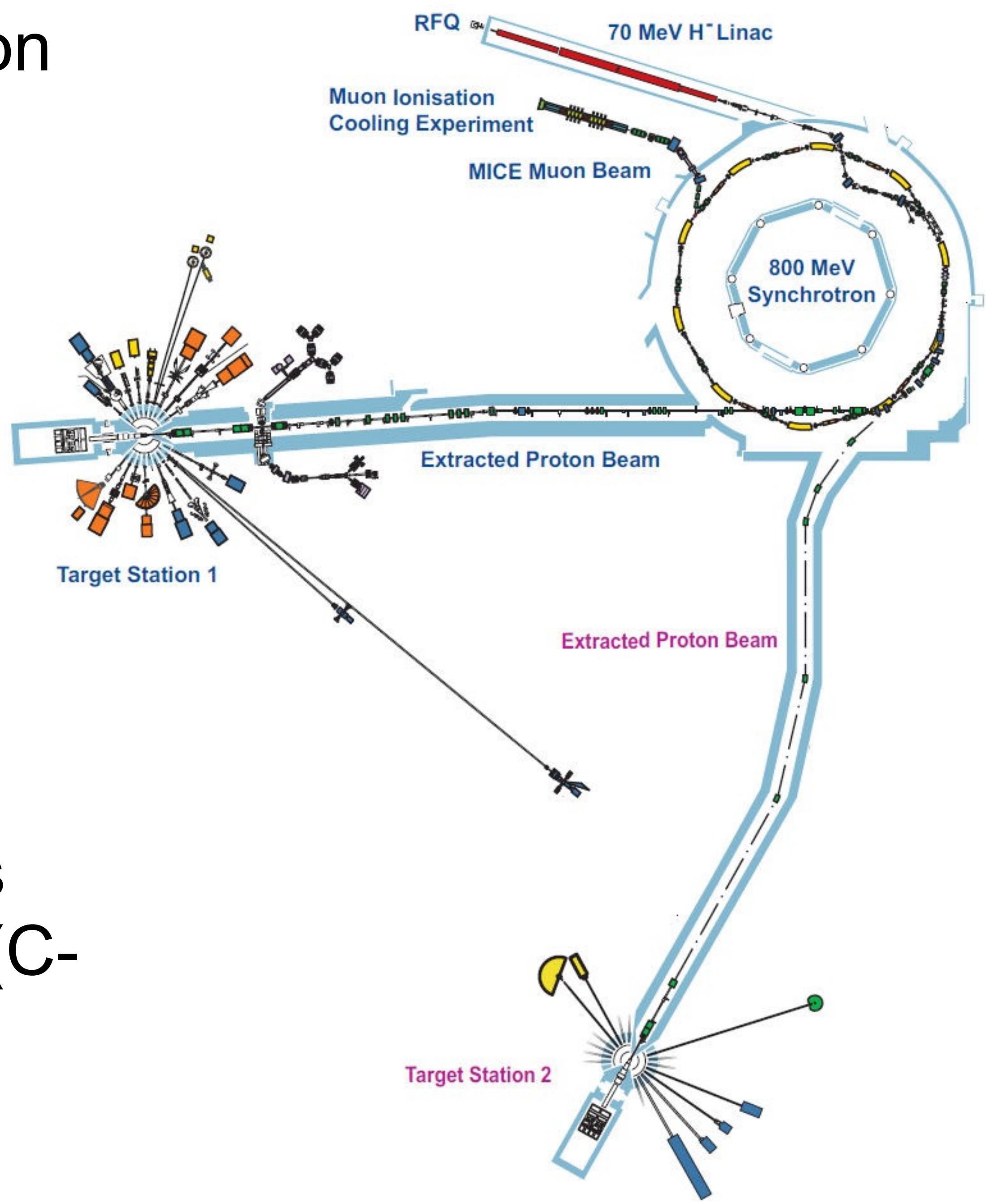
Background

- 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 from the developments at future facilities overseas, particularly in China (C-ADSR, C-HIAF, C-SNS)



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FFAG Option Models

- FFAG pumplet lattices
  - scaling and non-scaling
- RCS FFAG pumplet models
- Racetrack lattices
- DF-spiral models

- Designs for
  - main ring with radius of 52m, 31m, 26m, 25m
  - test ring with radius of 2.6m, 5m

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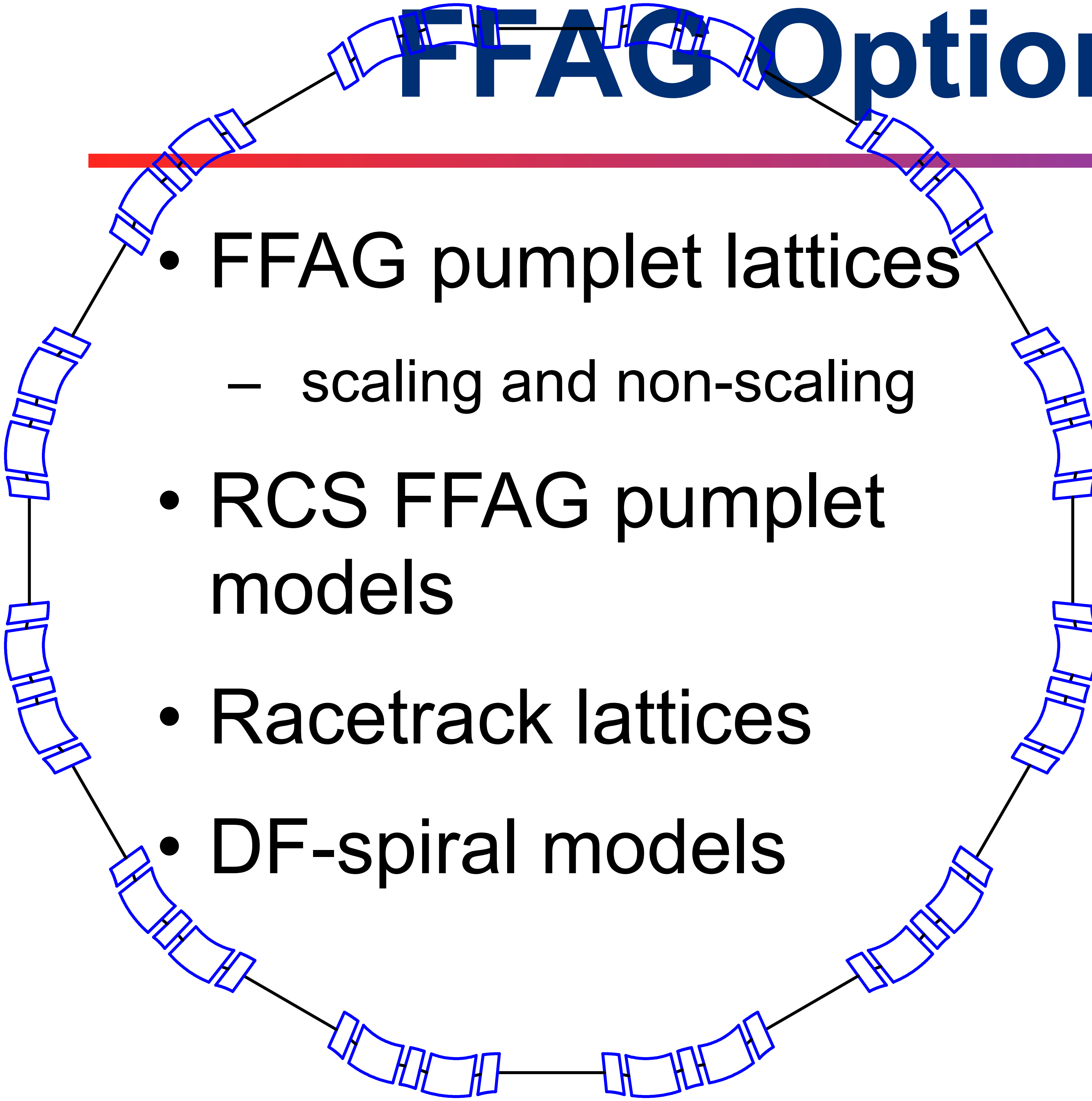

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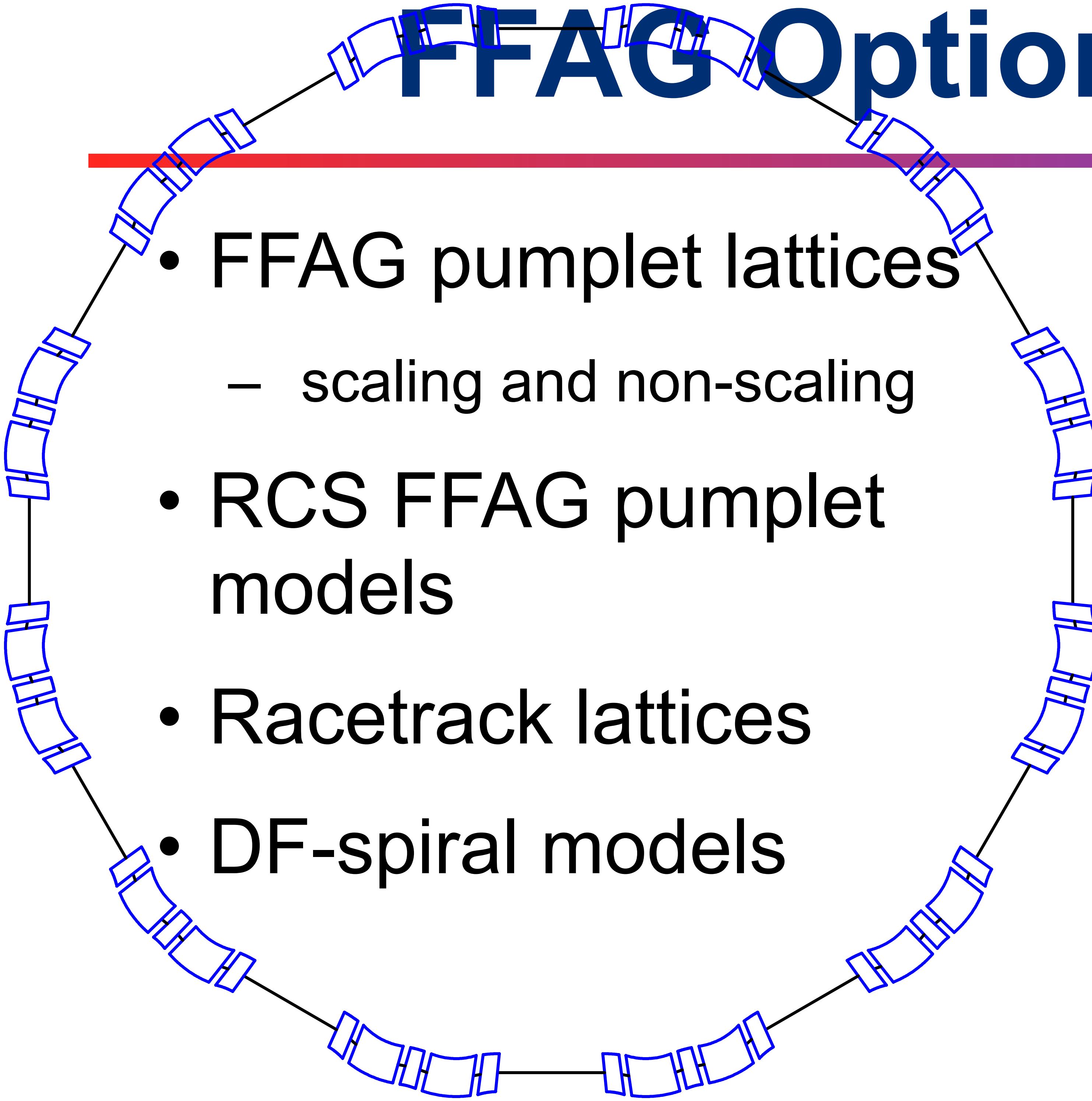

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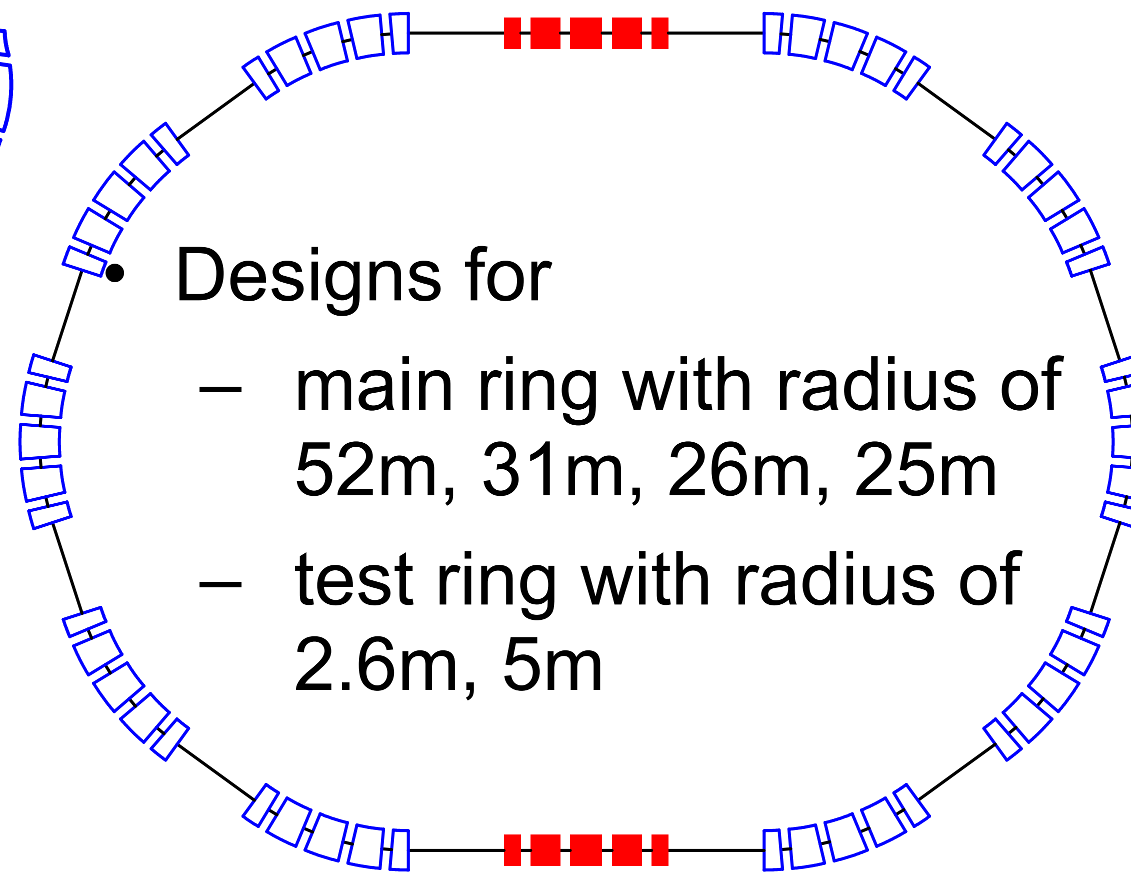

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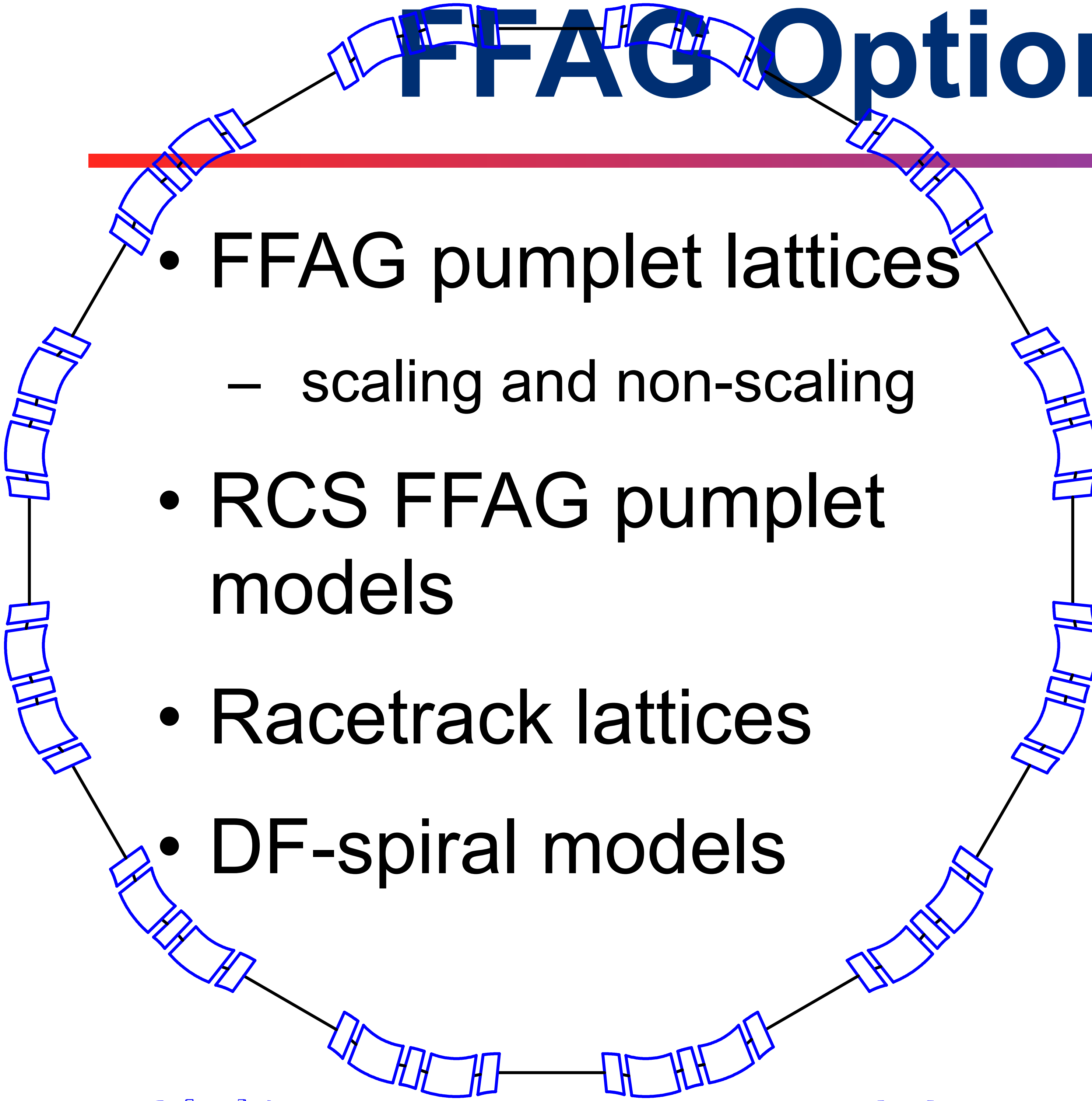

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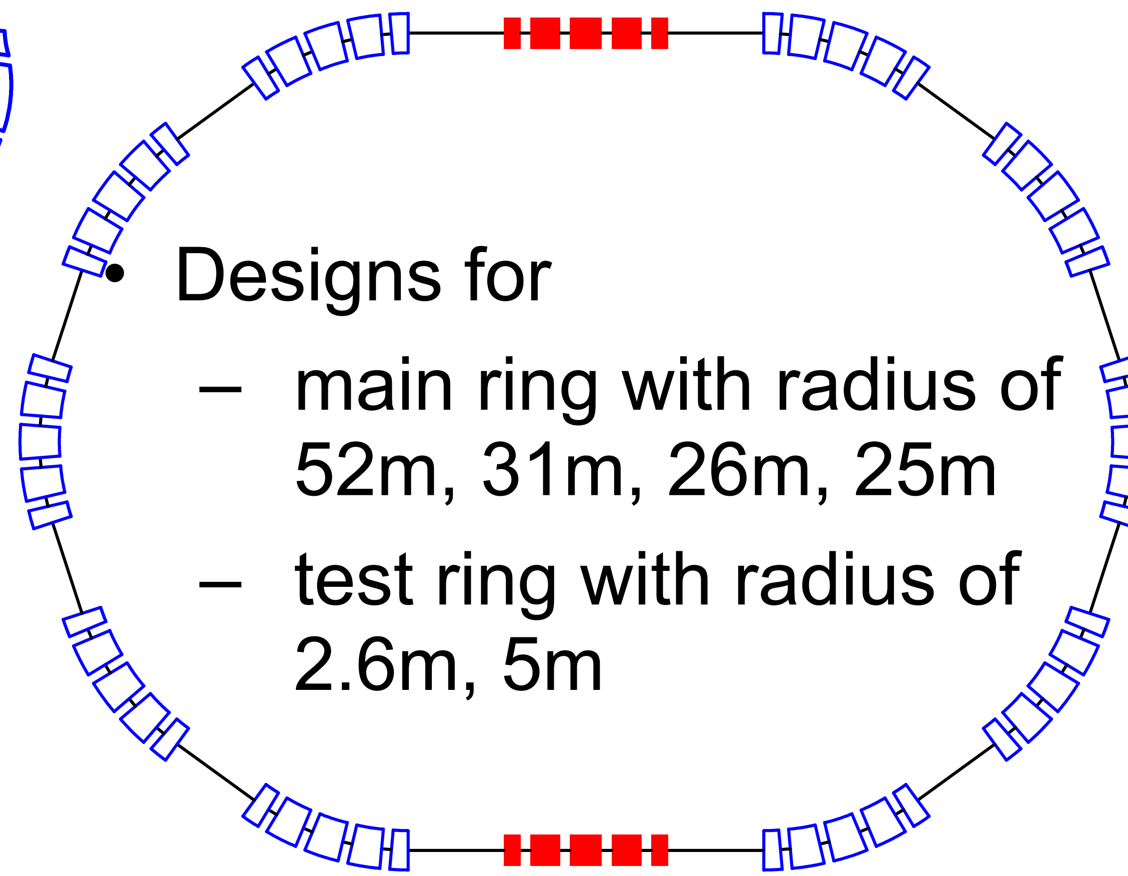

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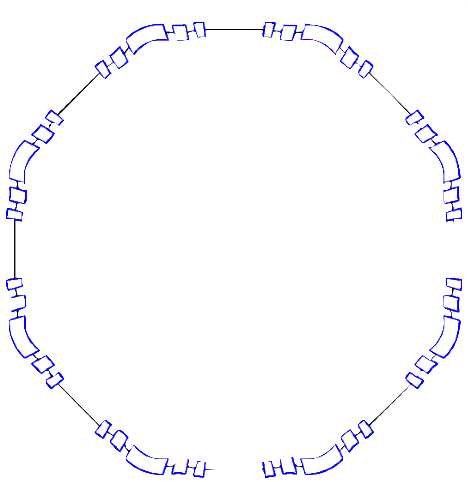

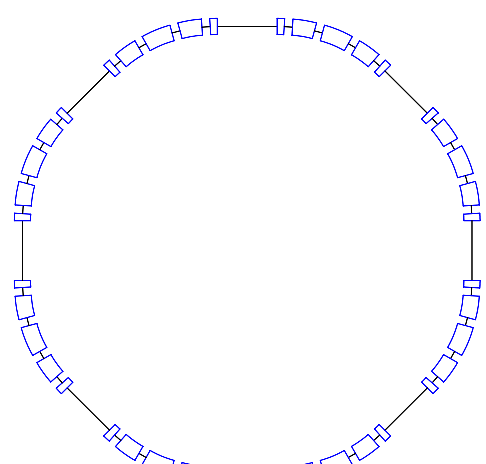

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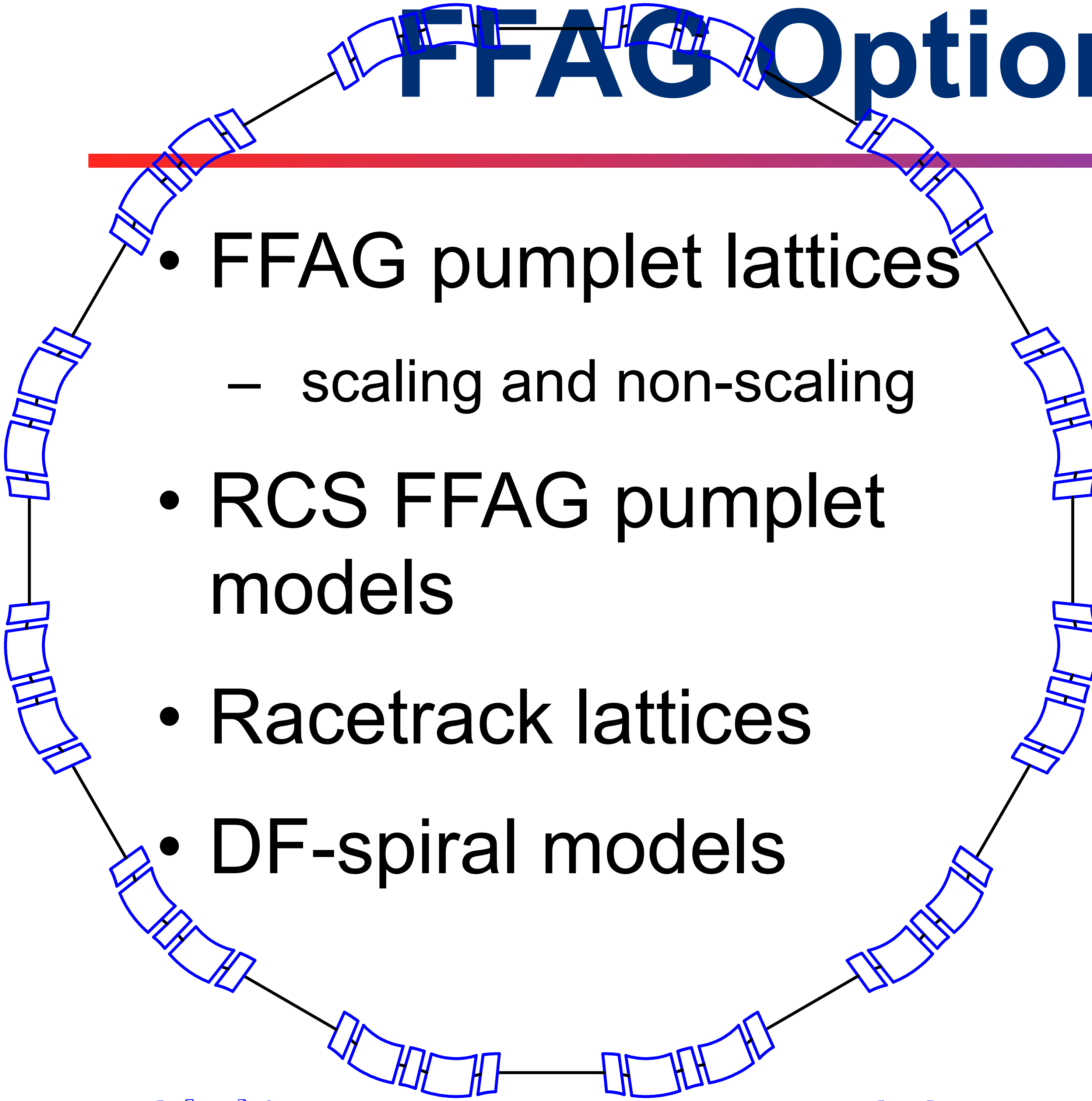

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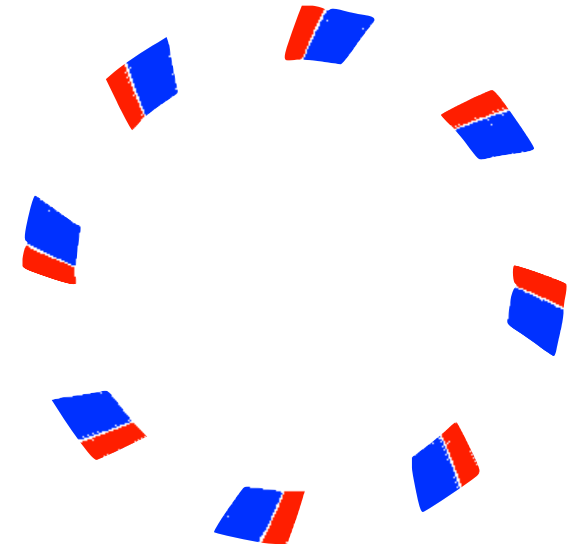

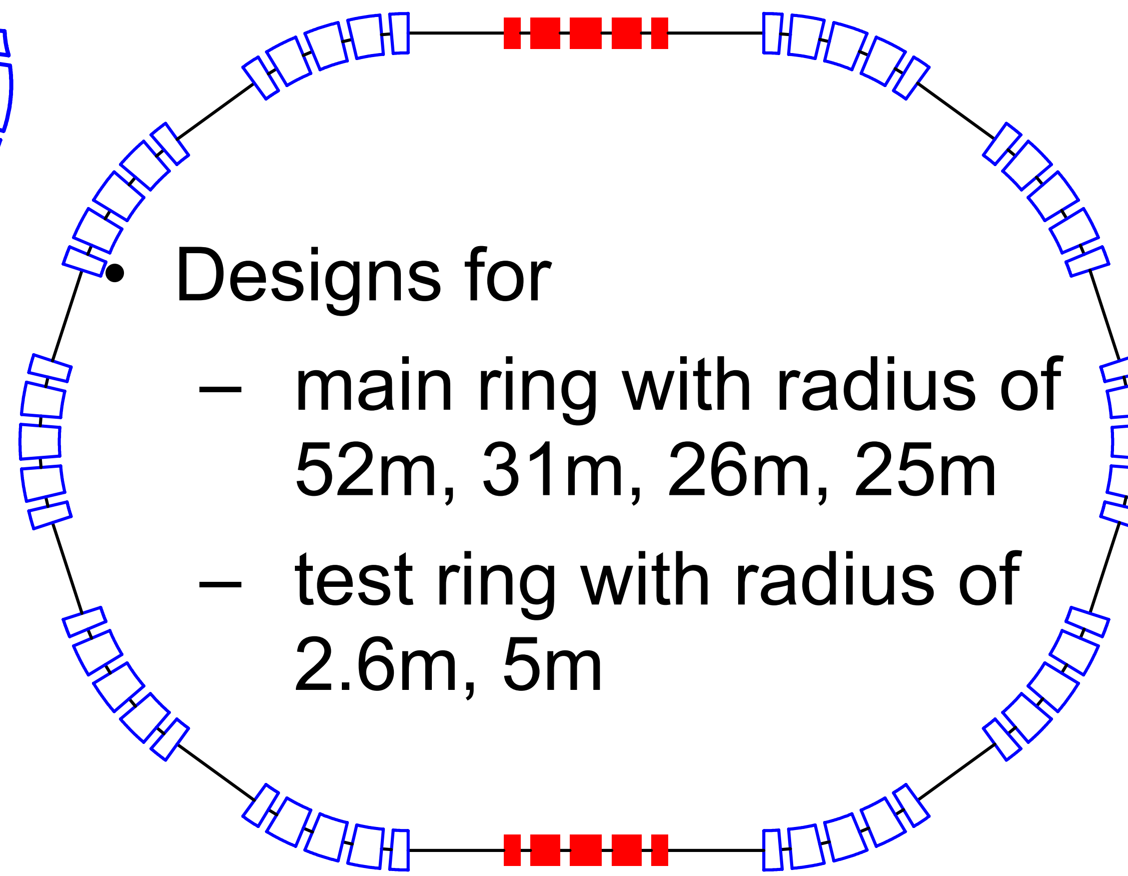

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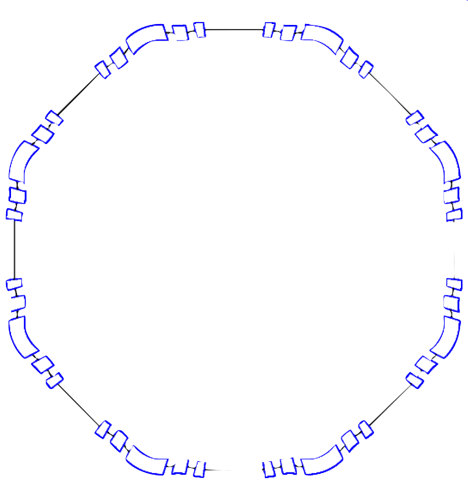

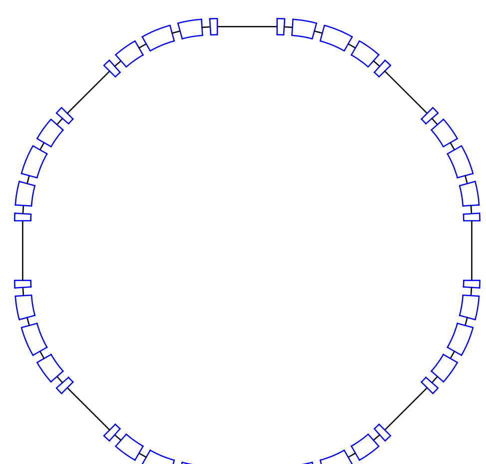

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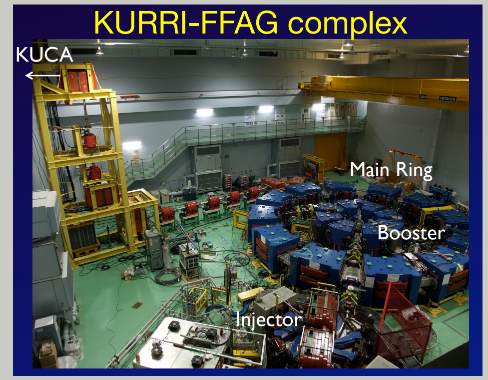
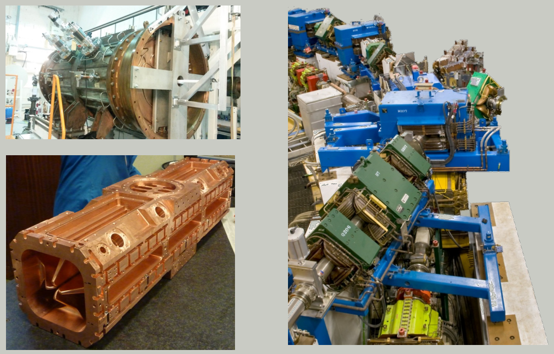
All models have direct proton injection for a multi-megawatt beam production

Studies of intense proton driver at RAL

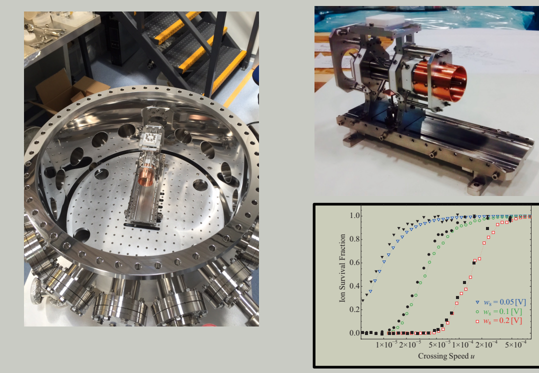
KURRI Collaboration



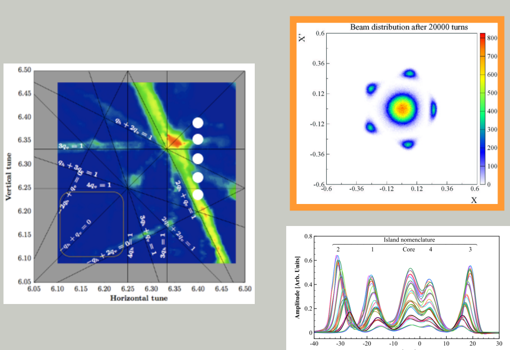
ISIS Spallation Source



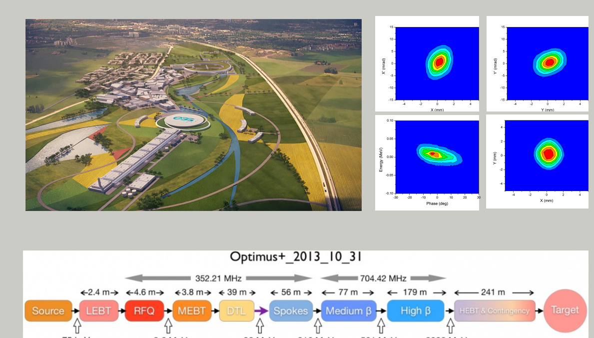
IBEX Paul Trap



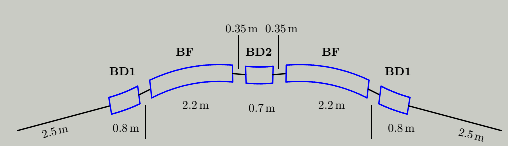
CERN LHC Injector Upgrade



European Spallation Source



Future UK Spallation Source



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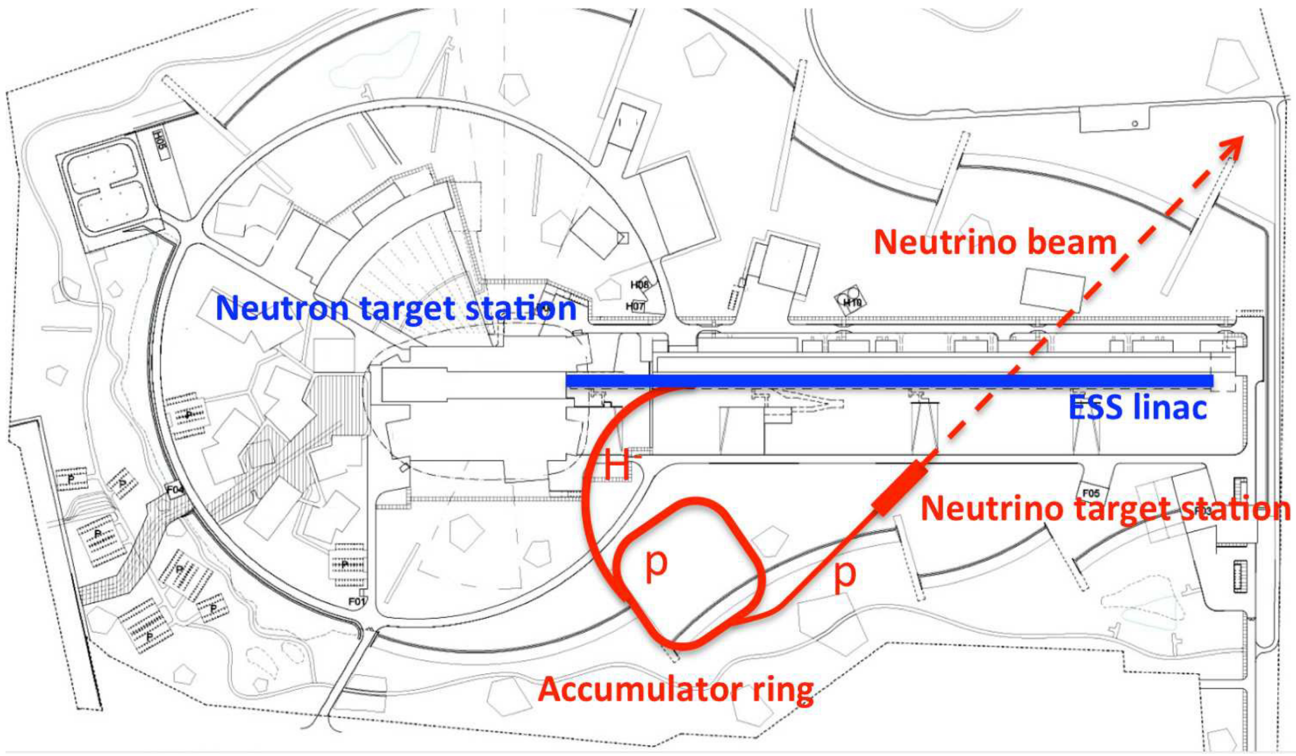
ESSnuSB

- Proposal to add a neutrino facility to the ESS linac



ESS linac output parameters:

Beam energy	2.0	GeV
Pulse beam current	62.5	mA
Pulse duration	2.86	ms
Pulse repetition rate	14	Hz
Beam power	5	MW

Proposed Ring parameters:

Beam energy	2.0	GeV
Accumulated beam power	5	MW
Ring circumference/radius	376/60	m

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Parameters ESSnuSB

Injection Parameters

Accumulated beam power (MW)	5.00
Kinetic energy at injection (MeV)	2000.0
β	0.9476
γ	3.1316
$\beta\gamma$	2.9676
Linac beam current (mA)	62.50
Linac chopping factor	1.00
Repetition rate (Hz)	14.0
Total number of particles ($\times 10^{14}$)	11.146
Injection interval required, Ne/I (ms)	2.86
Revolution period at injection, t (μs)	1.32
Ring circumference (m)	375.73
Number of injected turns	2160

Single ring or 4 rings with 2.78×10^{14} protons in each.

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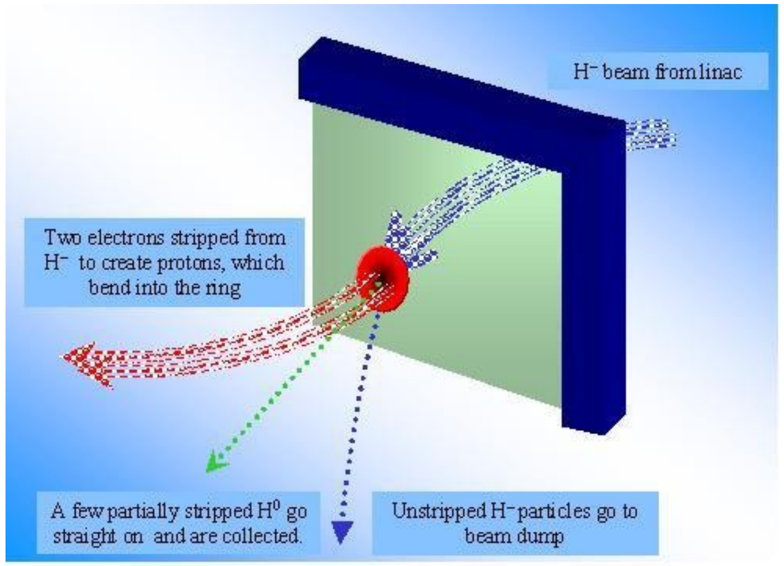
Beam Accumulation

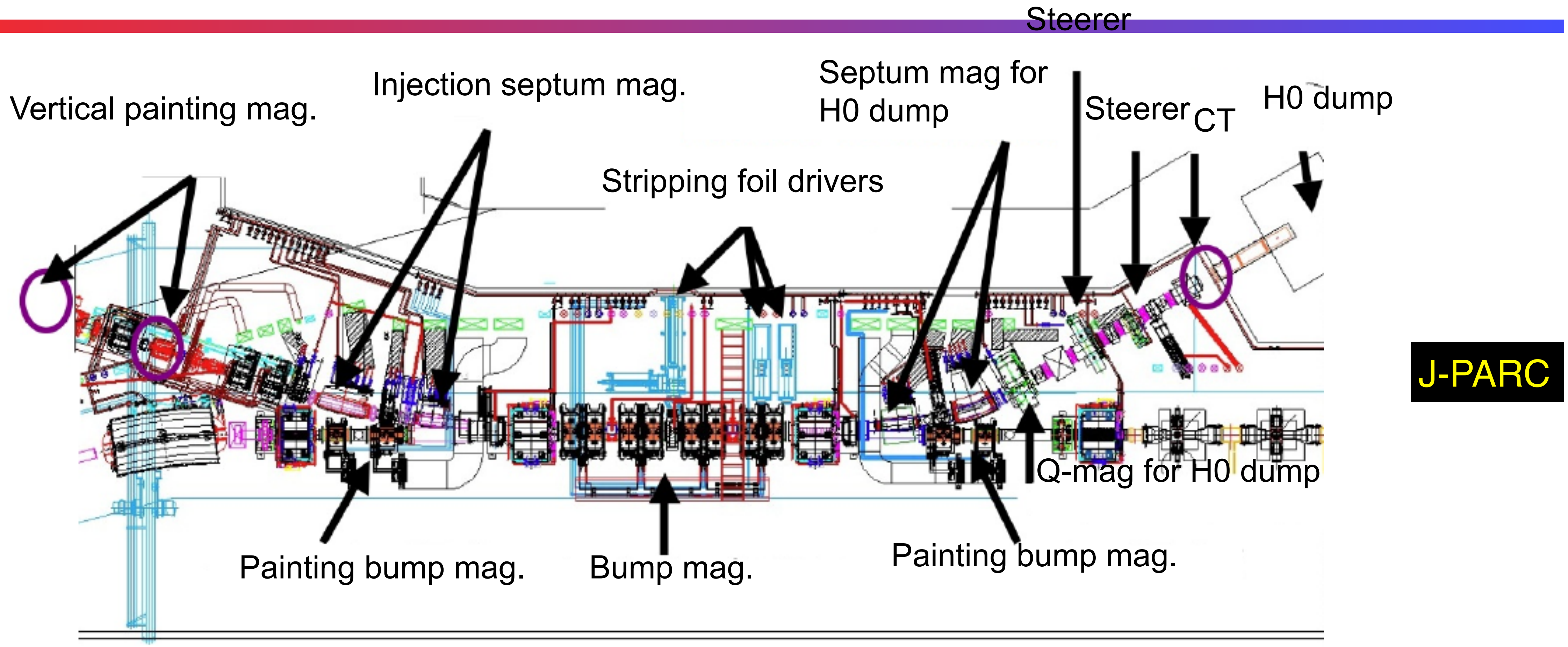
> *"The multiturn injection method by proton beam has been almost abandoned for injection from a linac to an RCS, due to its poor injection efficiency. H-minus stripping injection is a must to obtain highly accumulated protons in rings by hundreds of turns."*
>
> Reviews of Accelerator Science and Technology
> Volume 6: Accelerators for High Intensity Beams, April 2014

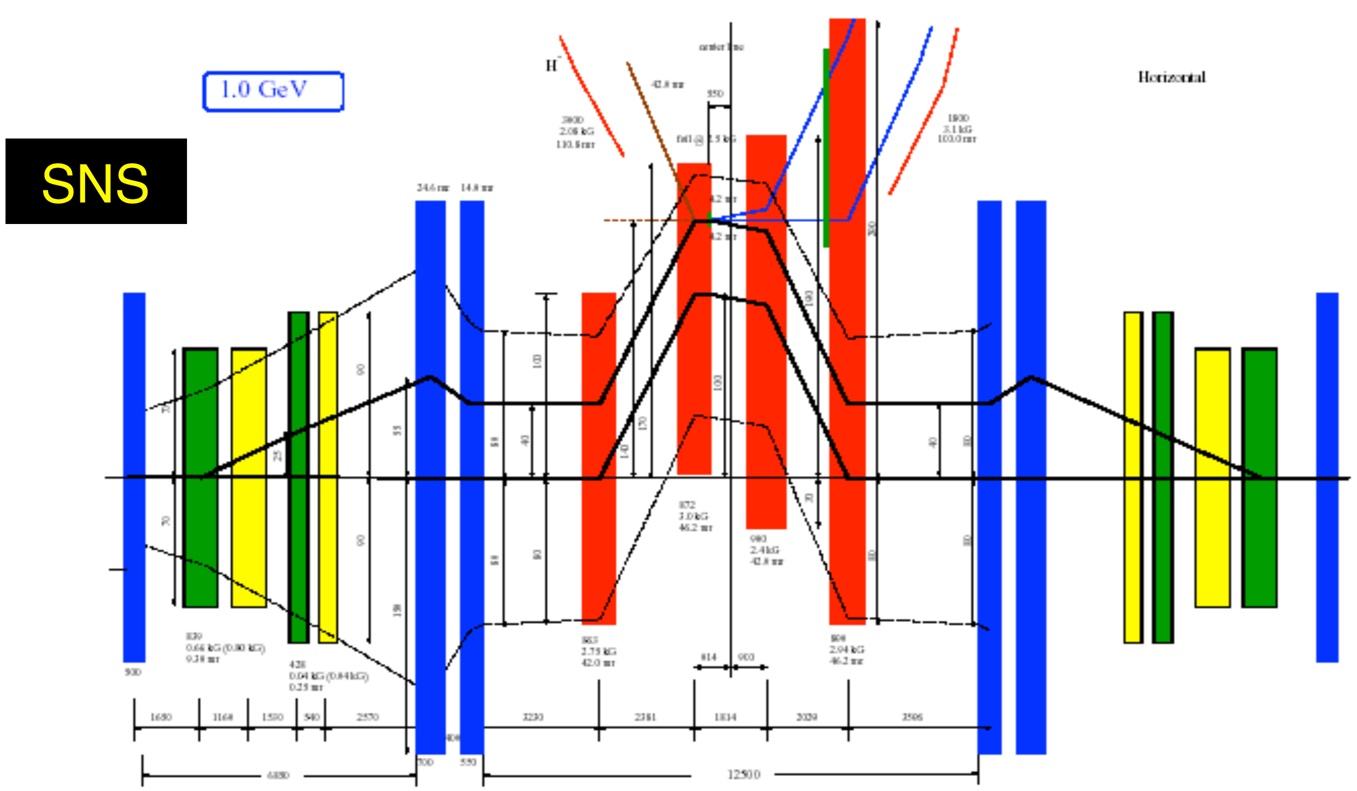
Downside



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

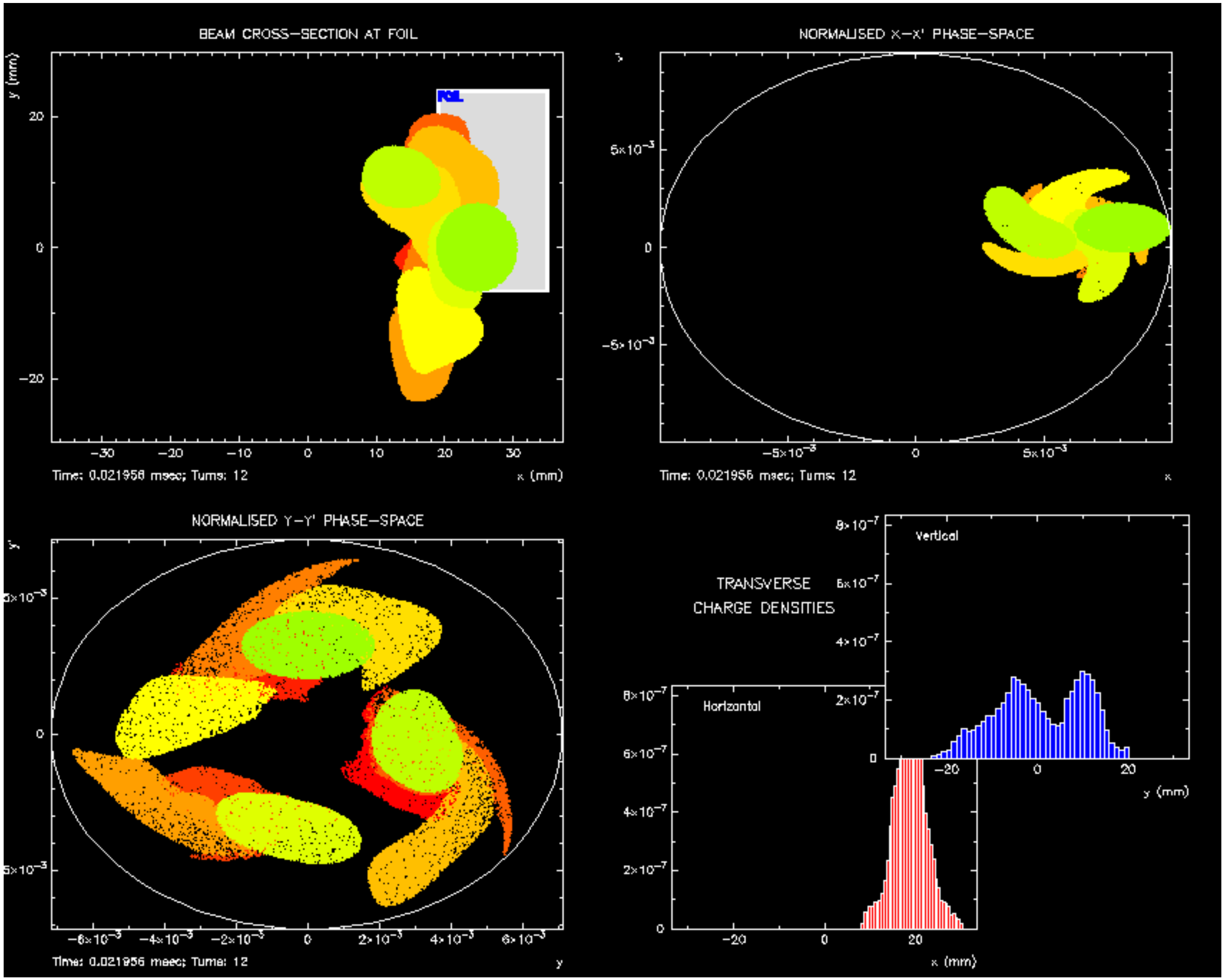
H⁻ Injection Regions





- J-Parc and SNS injection layouts.
- H and V bump magnets to paint the beam and reduce foil traversals.
- Can also use dispersion painting, injecting in a dipole.

Non-Liouvillean Injection



Optimising the closed orbit bumps to minimise the number of foil traversals is very like optimising to avoid beam loss for a Liouvillean system

H- injection modelling for a possible new 16 GeV booster ring for Fermilab (FNAL Driver Report, 2000)

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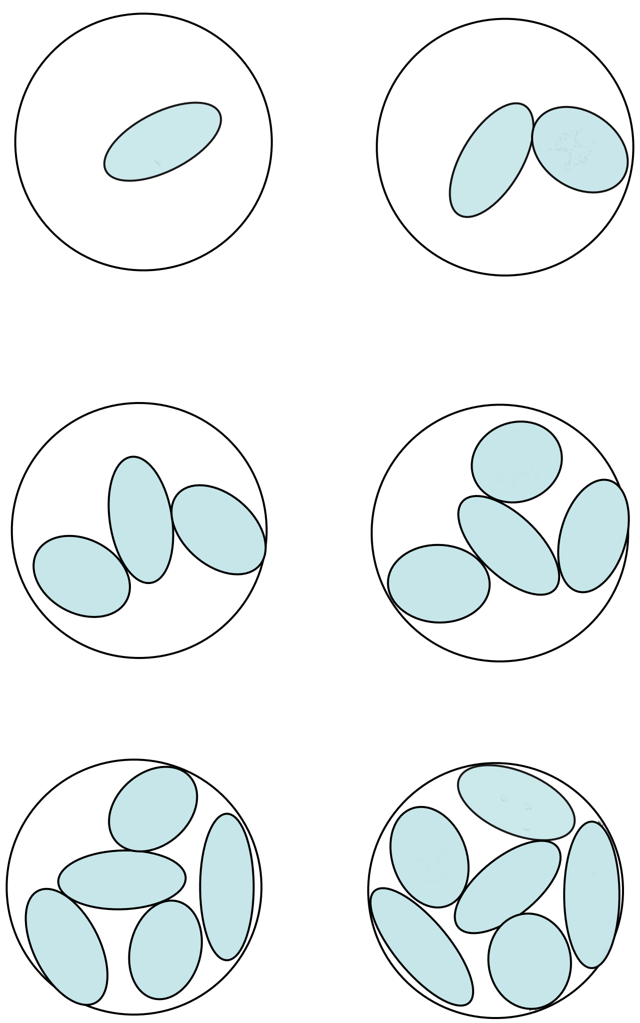
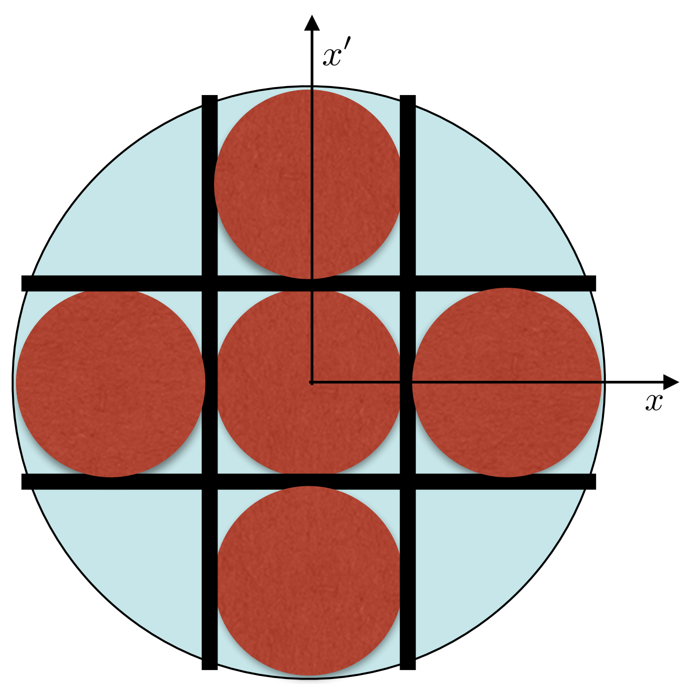
Direct Multiturn Injection

- Conventional method is to inject into one plane (h) and fill the other (v). Then (in some cases) rotate phase planes and repeat.
- Phase space has to be conserved (Liouville)



Optimised 6-turn injection scheme, Q=0.391 (C.Prior, 1980)



5-turn injection with Q=0.25: less than 5/9 of phase space occupied by beam, dilution F>9/5=1.8

Optimised schemes from 1980 study

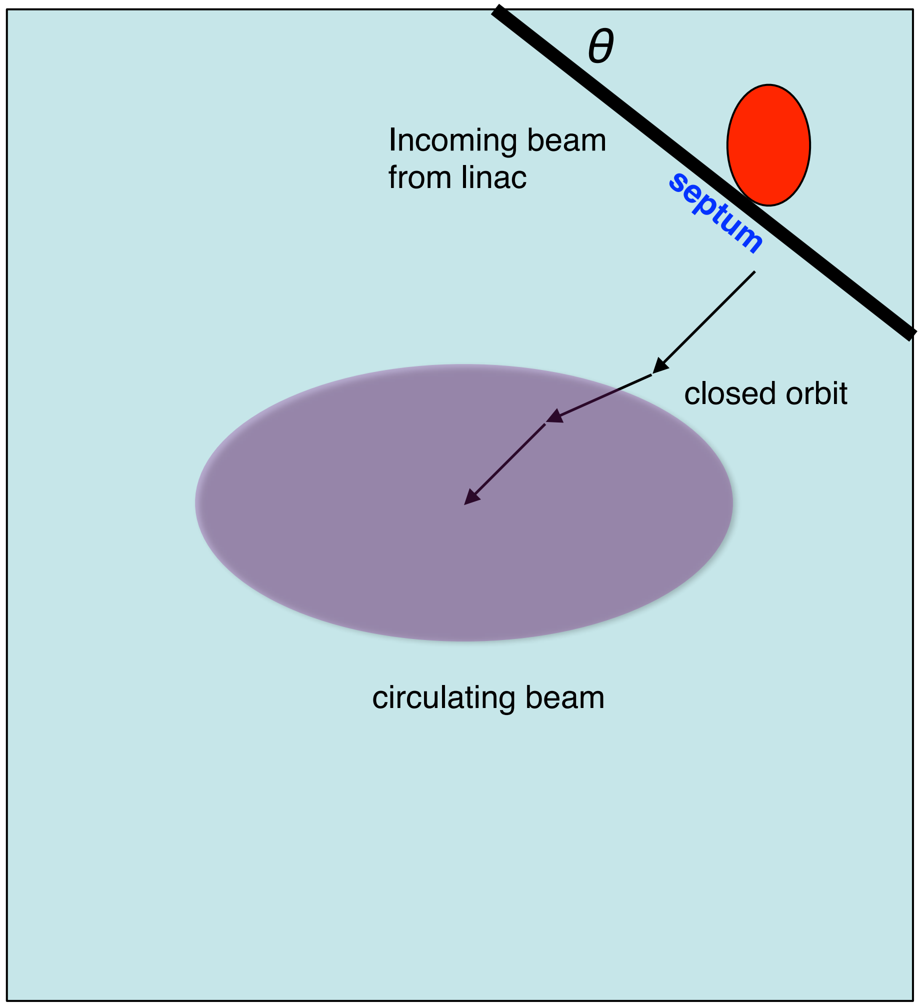
Number of turns	Dilution F
6	1.56
7	1.92
8	1.86
9	2.01
10	2.15

Expected number of injection turns $N \approx \frac{1}{F} \frac{\epsilon_{\text{ring}}}{\epsilon_{\text{inj}}}$

where F is the phase space dilution factor

Multiturn Injection of Protons

- Liouvillean injection using a tilted electrostatic septum
- Simple injection chicane
- Injection simultaneously into 4D transverse phase space
- Optimise h and v closed orbit bumps to minimise beam loss
- Requires careful choice of septum angle θ and ring optics (tunes, β-functions at injection point).



- Earlier simulations for HIDIF suggest maximum number of turns is

$$N_{\max} \approx \frac{1}{F} \frac{(\epsilon_h \epsilon_v)_{\text{ring}}}{(\epsilon_h \epsilon_v)_{\text{inj}}} \qquad \text{where} \qquad F \approx 20$$

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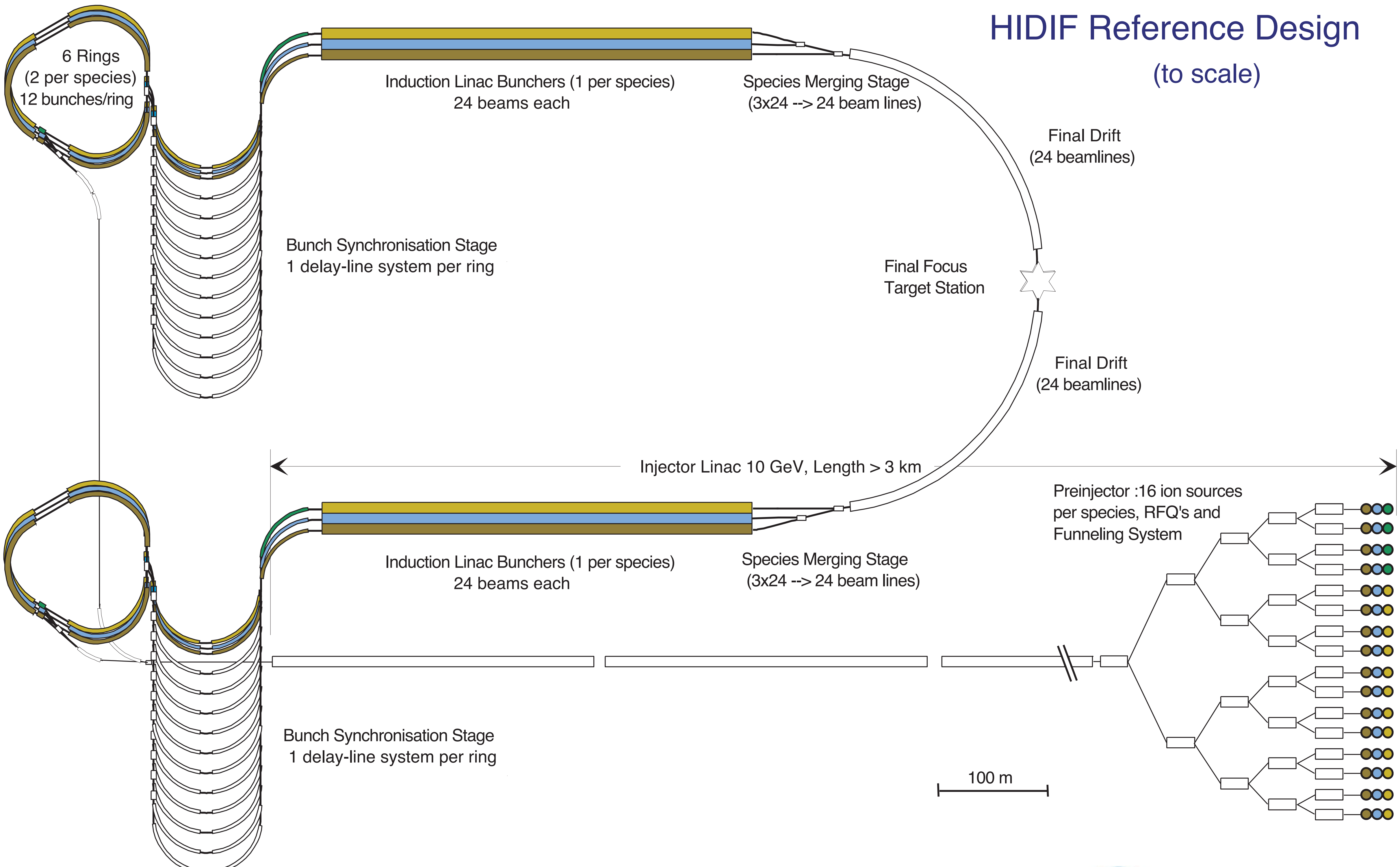
HIDIF Project 1996-2000



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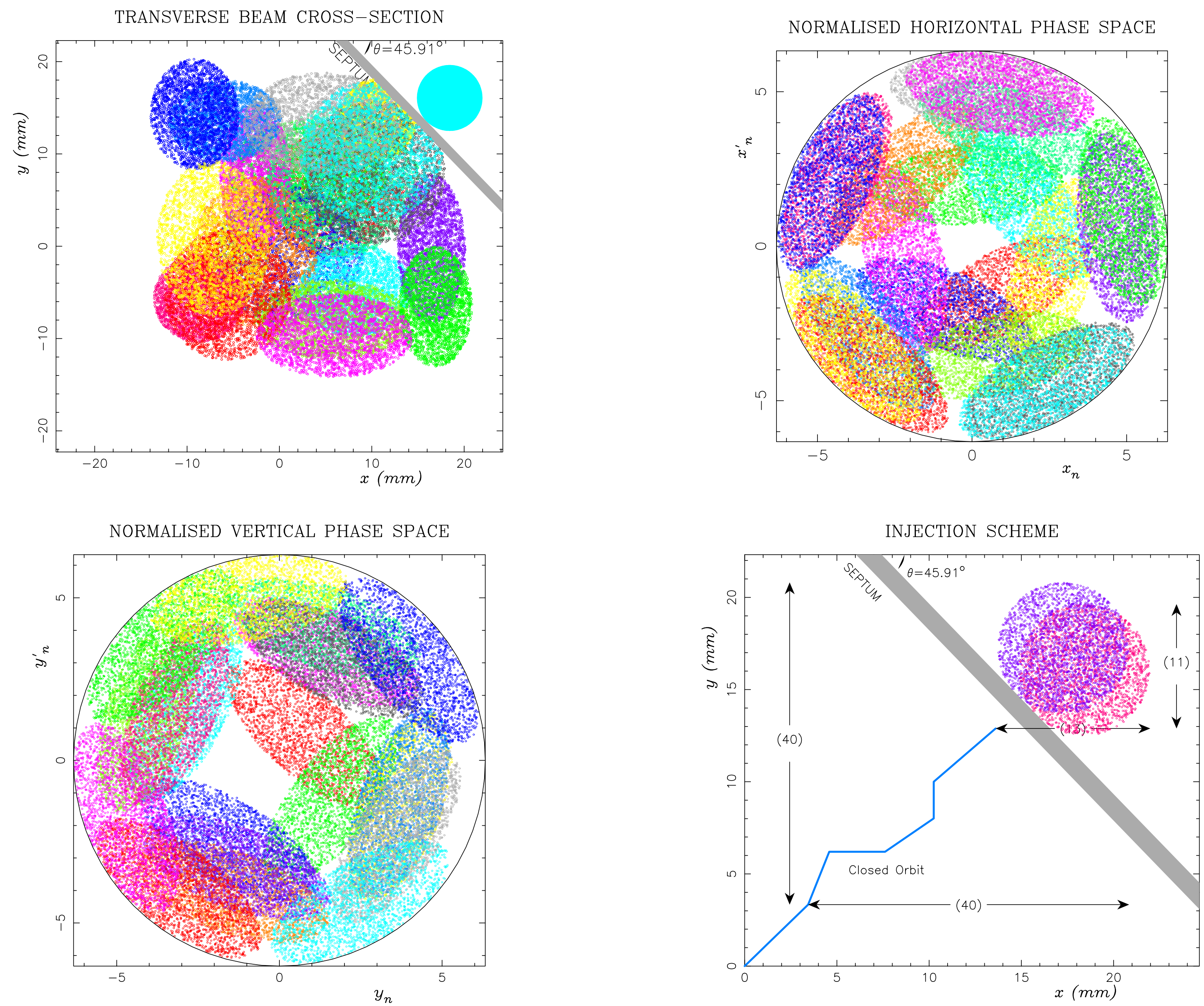
2-Plane Liouvillean Injection

- Obeys Liouville's theorem, preserving volumes in phase space.
- Tilted electrostatic septum at angle θ
- Orbit bumps in transverse plane to avoid beam loss at septum
- Correlated painting
- HIDIF: 20 turns, ε_{inj}=4 into ε_{ring}=40 (mm.mrad)

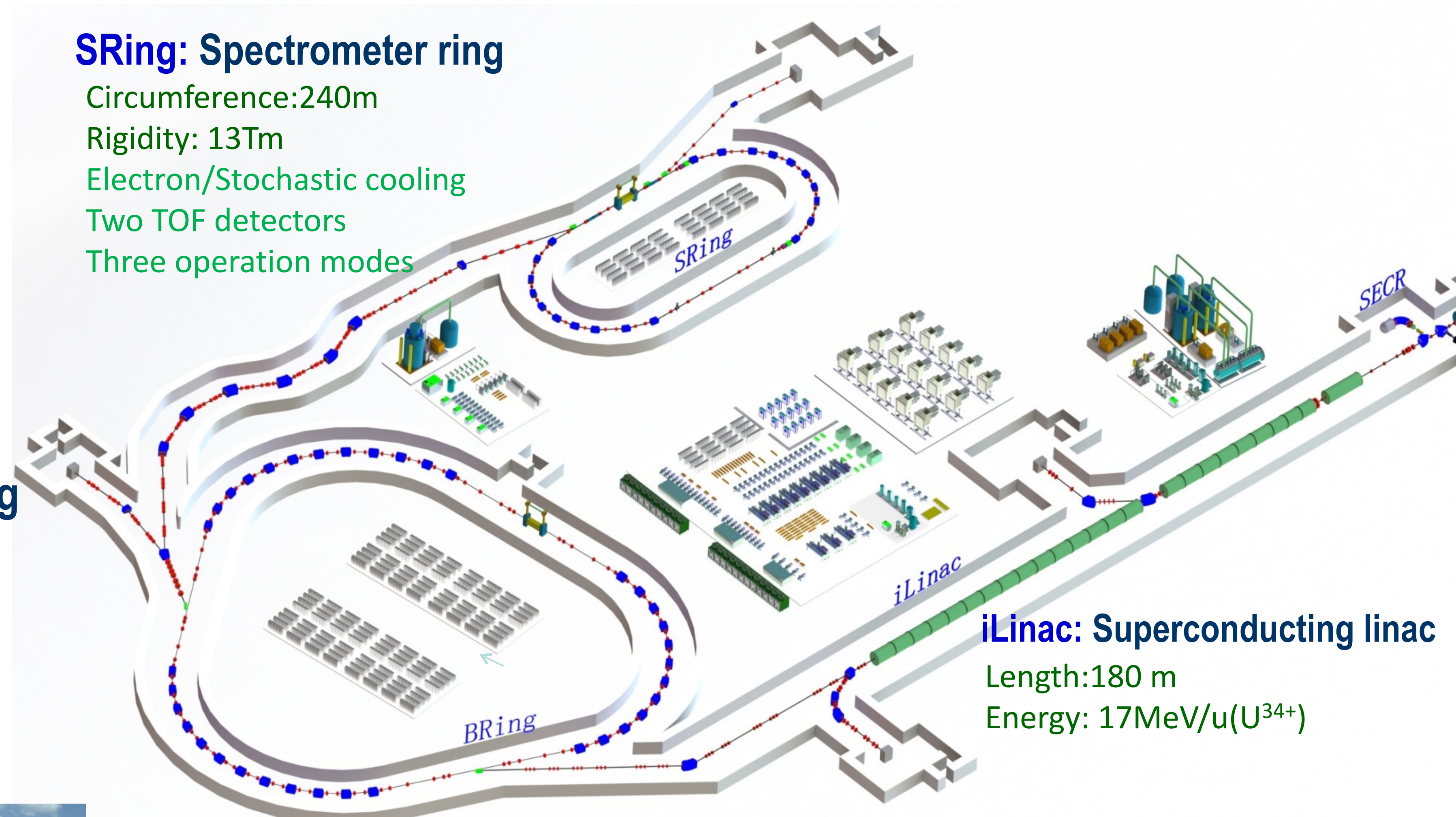


Injection scheme for HIDIF, 1998, (Bi^{+1})

Chinese HIAF

The Chinese High Intensity Heavy Ion Accelerator Facility, HIAF, to be built in Huizhou, will use the tilted septum injection scheme.

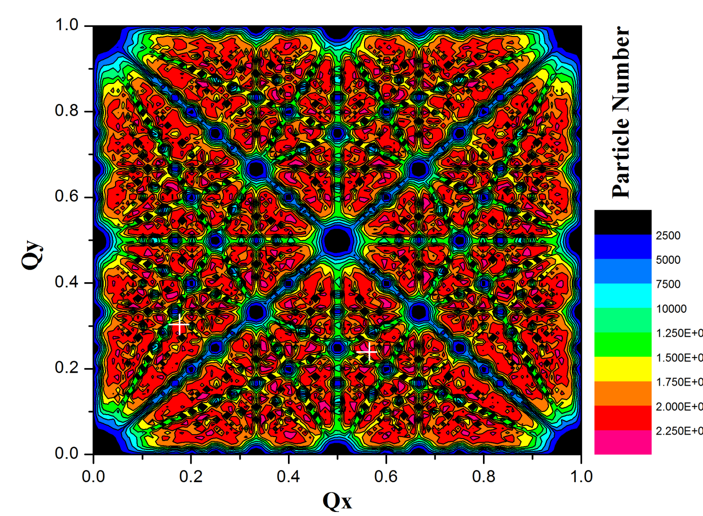
HIAF site

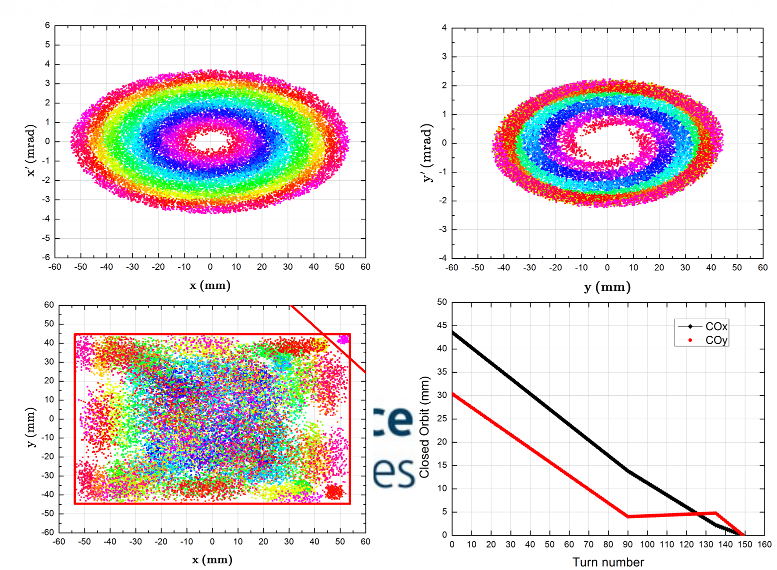


SRing: Spectrometer ring
- Circumference:240m
- Rigidity: 13Tm
- Electron/Stochastic cooling
- Two TOF detectors
- Three operation modes

BRing: Booster ring
- Circumference: 531.2 m
- Rigidity: 34 Tm
- Beam accumulation
- Beam cooling
- Beam acceleration

iLinac: Superconducting linac
- Length:180 m
- Energy: 17MeV/u(U^{34+})





MIS-codes

- MIS=Multi-turn Injection Scheme
- No space charge, geometric problem
- Requires only knowledge of optical parameters at injection point.
- MISHIF - main code
  - optimises θ, finds closed orbit variation over injection cycle, also suggests improved ring parameters
  - minimises phase space volume that falls on wrong side of septum
- MISOPT - refined optimisation
  - based on Harwell subroutines
  - Alternative MISPRAX uses new version of old praxis routine
- MISPLOT - graphical output
  - generates particles to fit optimised scheme; standard matrix transport
  - able to identify beam loss
- MISTRACK, MISKVBL
  - generate relevant parts of input datasets for lattice code and 2D(transverse) tracking code Track2D.

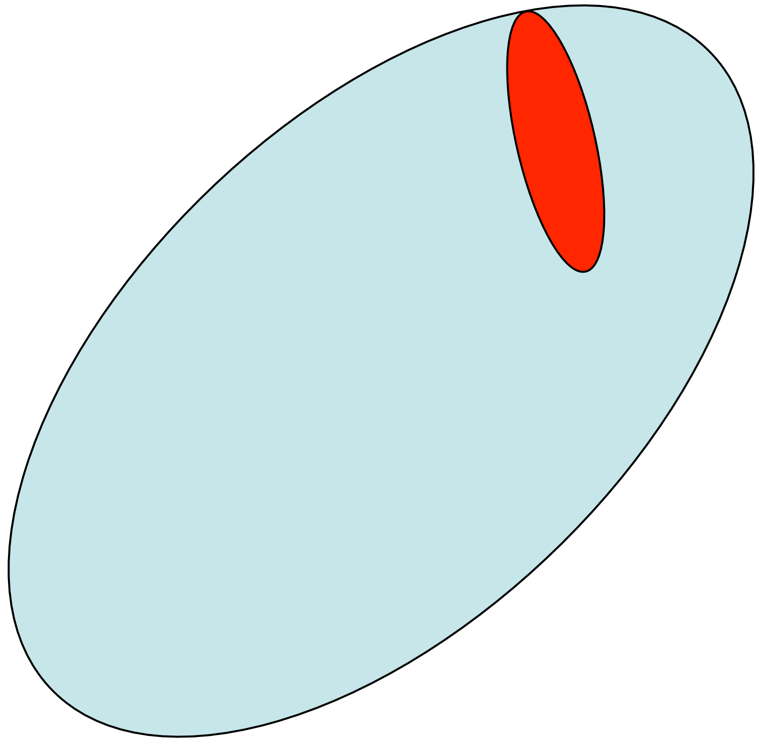
Preferred Conditions for Injection

- Two conditions desirable to minimise phase space wastage:

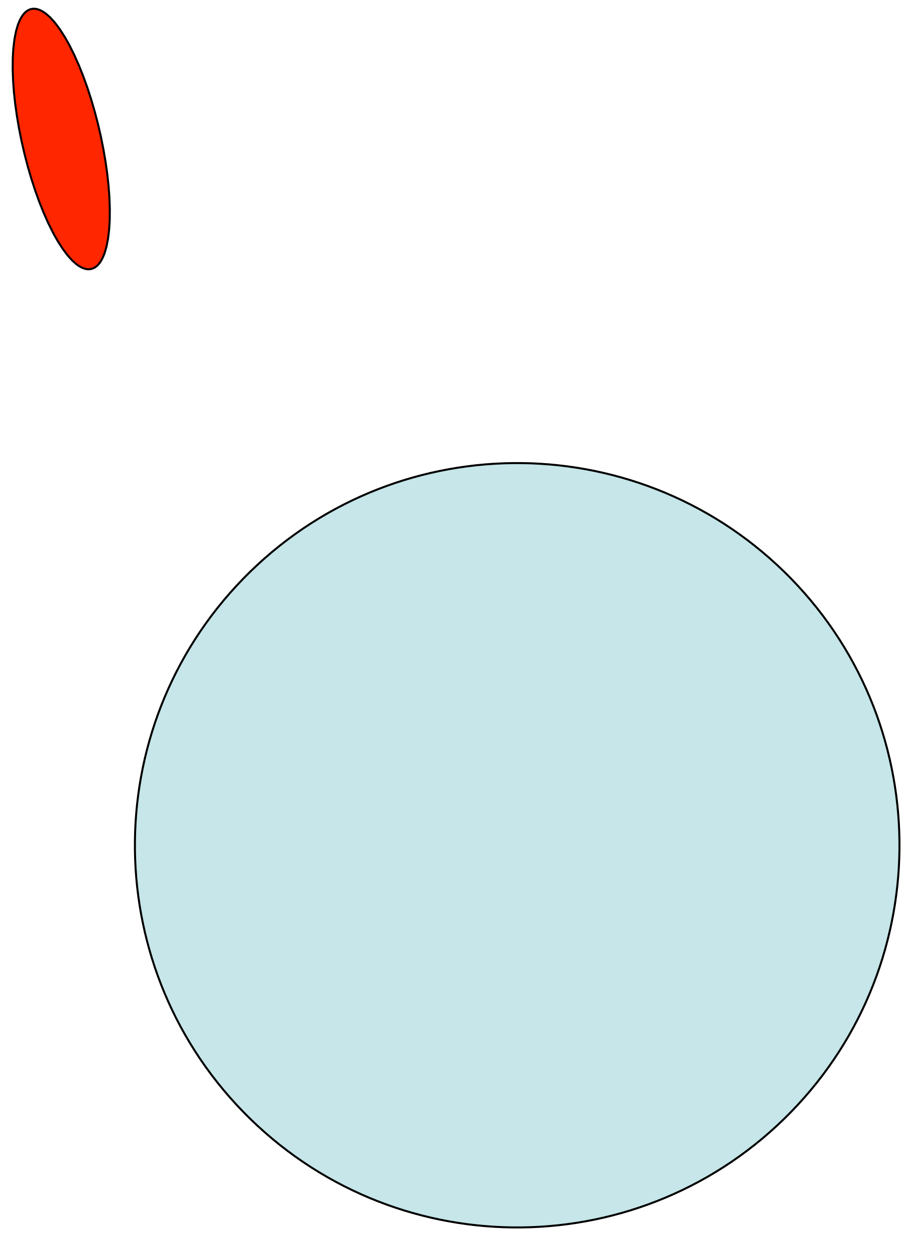
$$\text{(i)} \quad \frac{\beta}{\beta_i} \leq \left(\frac{\epsilon}{\epsilon_i}\right)^{\frac{1}{3}}$$

$$\text{(ii)} \quad \frac{\alpha_i}{\beta_i} = \frac{\alpha}{\beta} = -\frac{x_i' - x_o'}{x_i - x_o}$$

- where subscripts i and o refer to the injected turn and the closed orbit respectively.
- MIS-codes incorporate these by default (can be switched off)
- Codes also include option on painted distribution (e.g. as uniform as possible)

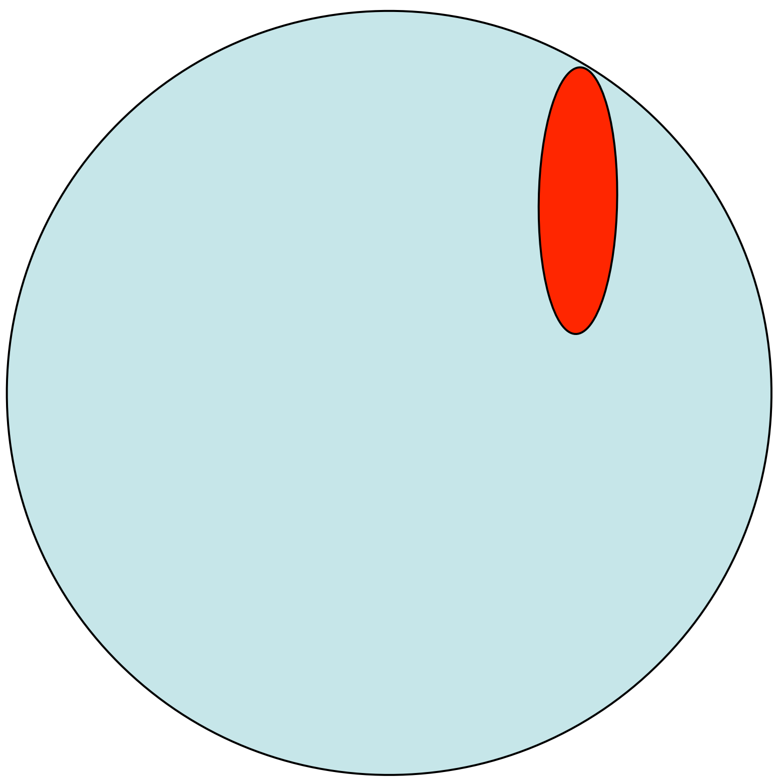


1. Working in normalised phase space, ring acceptance becomes circular



1. Working in normalised phase space, ring acceptance becomes circular

2. Condition $\frac{\alpha_i}{\beta_i} = \frac{\alpha}{\beta}$ makes the injected turn upright



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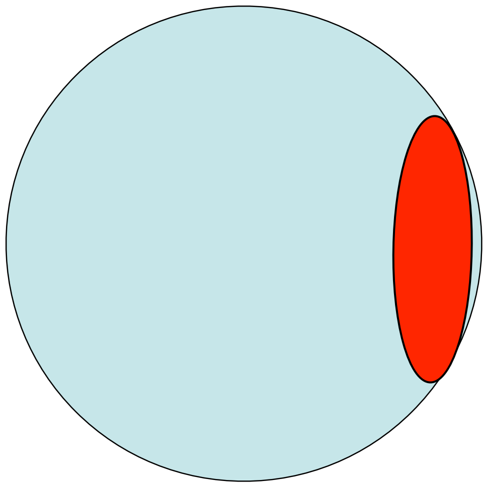

3. Adding in $\frac{\alpha_i}{\beta_i} = \frac{\alpha}{\beta} = -\frac{x_i' - x_o'}{x_i - x_o}$ places the turn on axis and reduces the ring emittance

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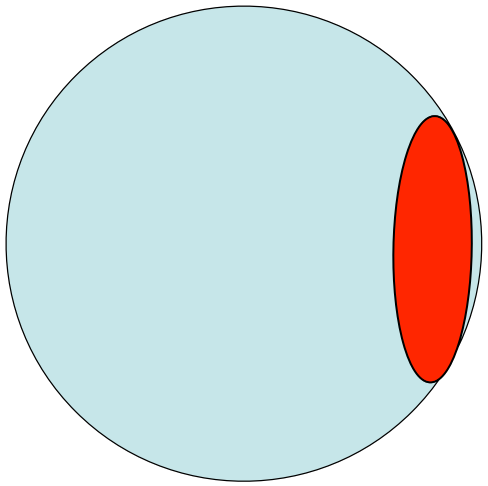

3. Adding in $\frac{\alpha_i}{\beta_i} = \frac{\alpha}{\beta} = -\frac{x_i' - x_o'}{x_i - x_o}$ places the turn on axis and reduces the ring emittance

4. Condition $\frac{\beta}{\beta_i} \leq \left(\frac{\epsilon}{\epsilon_i}\right)^{\frac{1}{3}}$ matches the curvatures to minimise wasted phase space

Implications for ESSnuSB

Injection Parameters

Kinetic energy at injection (MeV)	2000.0
Linac proton beam current (mA)	62.50
Linac 1σ normalised emittance (π mm.mrad)	0.25
Unnormalised (3σ) injected emittances (π mm.mrad)	0.76
Painted emittances of ring beam (π mm.mrad)	100.00
Expected tune depression	0.025
Number of particles N ($\times 10^{14}$)	2.82
Linac chopping factor	1.00
Bunching factor during injection	1.00
Injection interval, Ne/I (μs)	723.62
Revolution period at injection, t (μs)	1.32
Mean radius at injection energy, $\beta ct/2\pi$ (m)	59.80
Number of injected turns	547

Assumes 4 rings and accumulates a total of 5.05 MW beam power, 1.26 MW in each ring.

$$\Delta Q_v = -\frac{N r_p}{\pi \epsilon_v \left(1 + \sqrt{\epsilon_h/\epsilon_v}\right) \beta^2 \gamma^3} \frac{1}{B_f}$$

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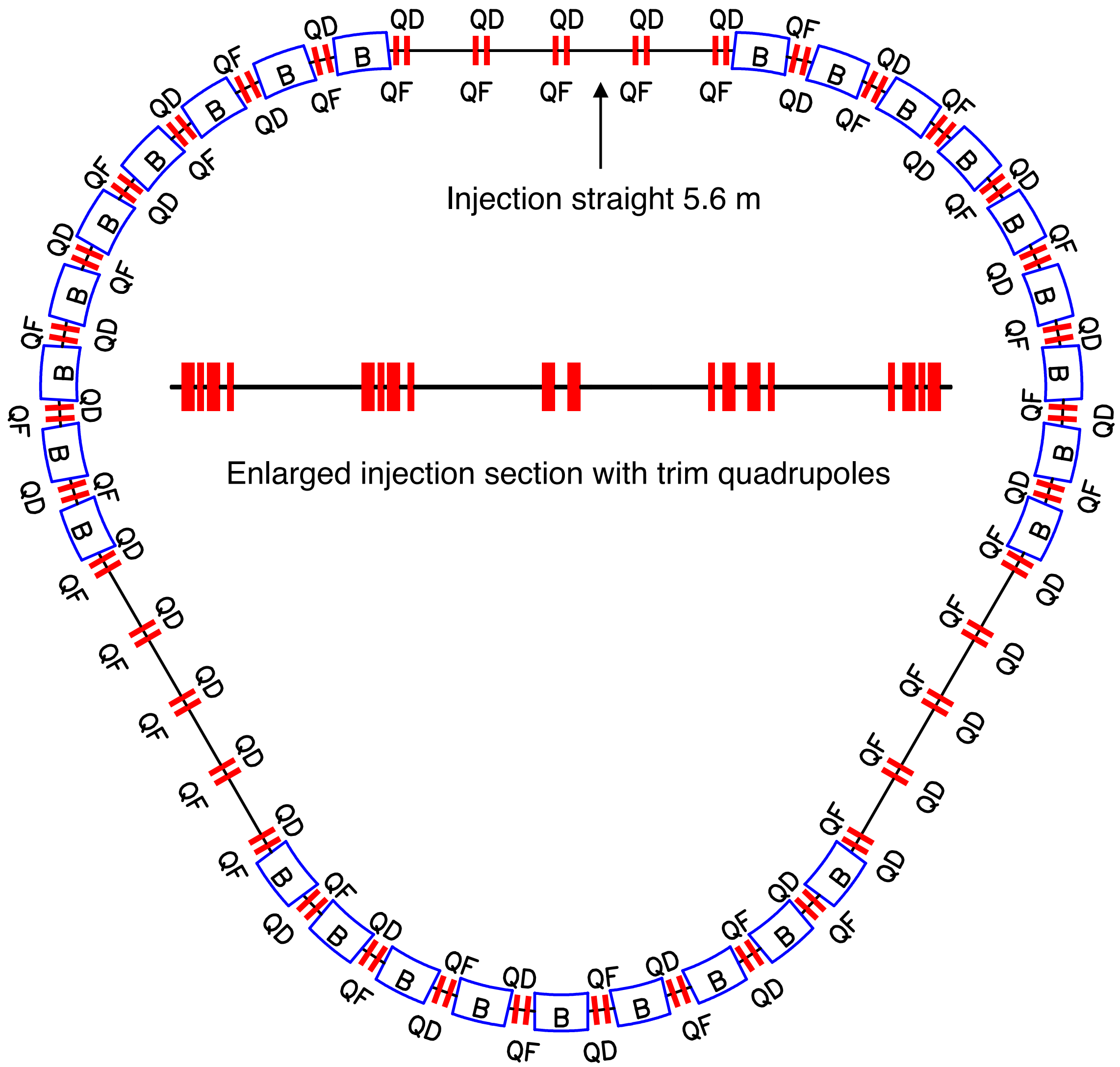
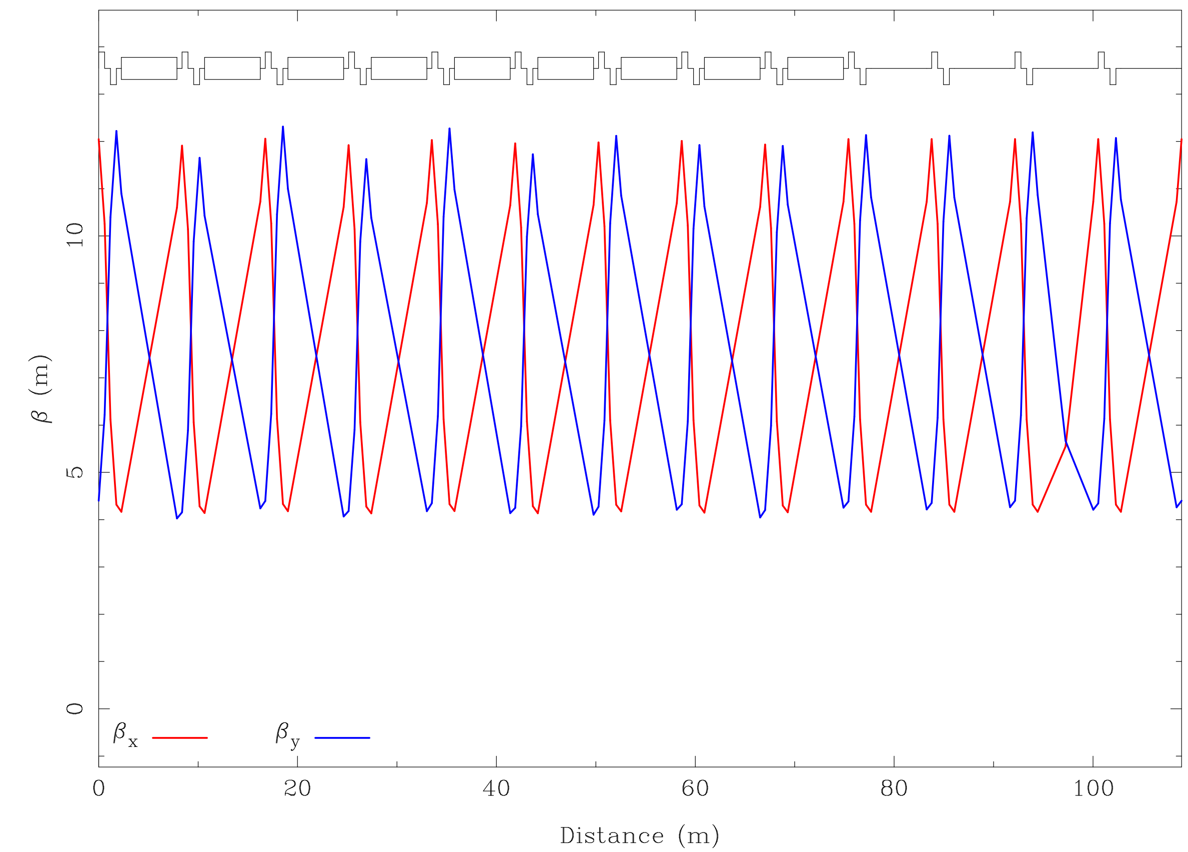
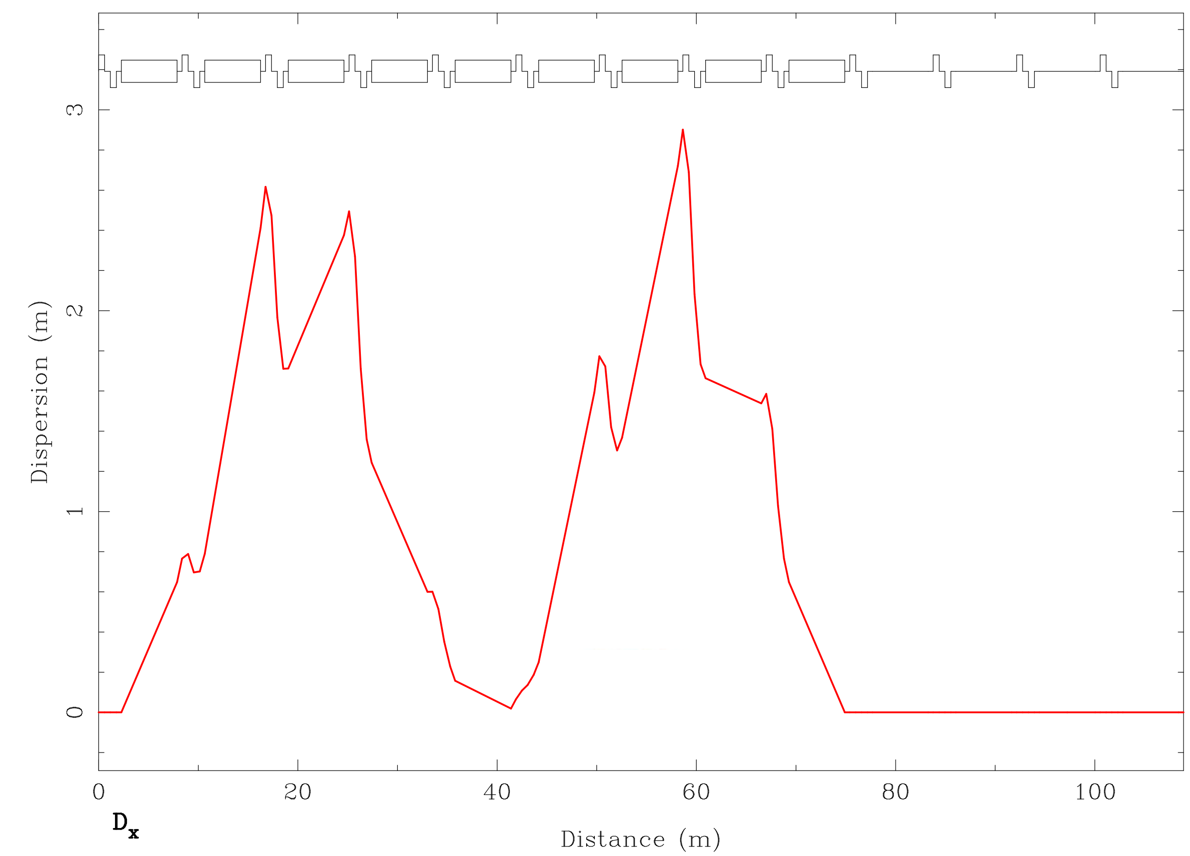
Example Ring







- Mean radius $R = 52\,\mathrm{m}$
- $\beta_{\mathrm{max}} \approx 12\,\mathrm{m}$, $\beta_{\mathrm{min}} \approx 4\,\mathrm{m}$
- Optical parameters at injection point:

$$\begin{aligned} \beta_x &= 5.547969, \quad \alpha_x = -0.585526 \quad (\alpha_x/\beta_x = -0.1055) \\ \beta_y &= 5.668059, \quad \alpha_x = 0.594398 \quad (\alpha_y/\beta_y = 0.1049) \end{aligned}$$

- Base tunes: $Q_x = 8.678324$, $Q_y = 8.706738$

Preferred Conditions

$$\frac{\beta}{\beta_i} \leq \left(\frac{\epsilon}{\epsilon_i}\right)^{\frac{1}{3}} = 5.0903 \qquad \Longrightarrow \qquad \begin{cases} \beta_{ix} \geq 1.0899 \\ \beta_{iy} \geq 1.1135 \end{cases}$$

$$\frac{x_i' - x_o'}{x_i - x_o} = -\frac{x_o'}{x_i - x_o} = -\frac{\alpha_x}{\beta_x} = \quad 0.10554 = -\frac{\alpha_{ix}}{\beta_{ix}}$$

$$\frac{y_i' - y_o'}{y_i - y_o} = -\frac{y_o'}{y_i - y_o} = -\frac{\alpha_y}{\beta_y} = -0.10487 = -\frac{\alpha_{iy}}{\beta_{iy}}$$

Optimised values from code for 500 turns:

- Machine tunes: $Q_x = 8.7436, Q_y = 8.8030$

c.f. bare tunes $Q_x = 8.6783, Q_y = 8.7067$

- Septum angle: $\theta = 44.75°$
- Injected turns: $\beta_{ix} = 1.3984, \alpha_{ix} = -0.1476, \beta_{iy} = 1.3092, \alpha_{iy} = 0.1373$
- Injected emittances: $\epsilon_{ix} = \epsilon_{iy} = 0.758\,\pi\,\text{mm.mrad}$

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First results - 500 turns

REV	CLOSED ORBIT		INJECTED BEAM		MACHINE PARAMETERS				BEAM EMITTANCES	
	x	y	x	y	β_x	β_y	α_x	α_y	ϵ_x	ϵ_y
1	27.2277	28.3963	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	13.8594	11.5512
60	23.6765	24.1538	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	26.5669	25.4612
120	22.5140	19.9114	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	31.7811	46.0798
180	20.0726	18.4127	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	44.4254	54.9670
240	17.6969	17.3540	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	58.8854	61.7499
300	15.1290	16.9142	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	76.8061	64.6874
360	12.8864	16.4160	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	94.4013	68.0972
420	12.2175	14.6556	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	100.0001	80.8479
450	12.2175	13.4570	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	100.0001	90.1548
500	12.2175	12.2547	34.7475	35.0714	5.5480	5.6681	-0.5855	0.5944	100.0001	100.0001

Total beam loss =0.658 %
(assuming uniform beam)

EQUATION OF SEPTUM $ax + by + c = 0$, with

$a = 0.704055, b = 0.710146, c = -47.362466$ (x and y in mm)

- Apart from closed orbit bumps, all parameters constant during injection
- Space charge forces omitted

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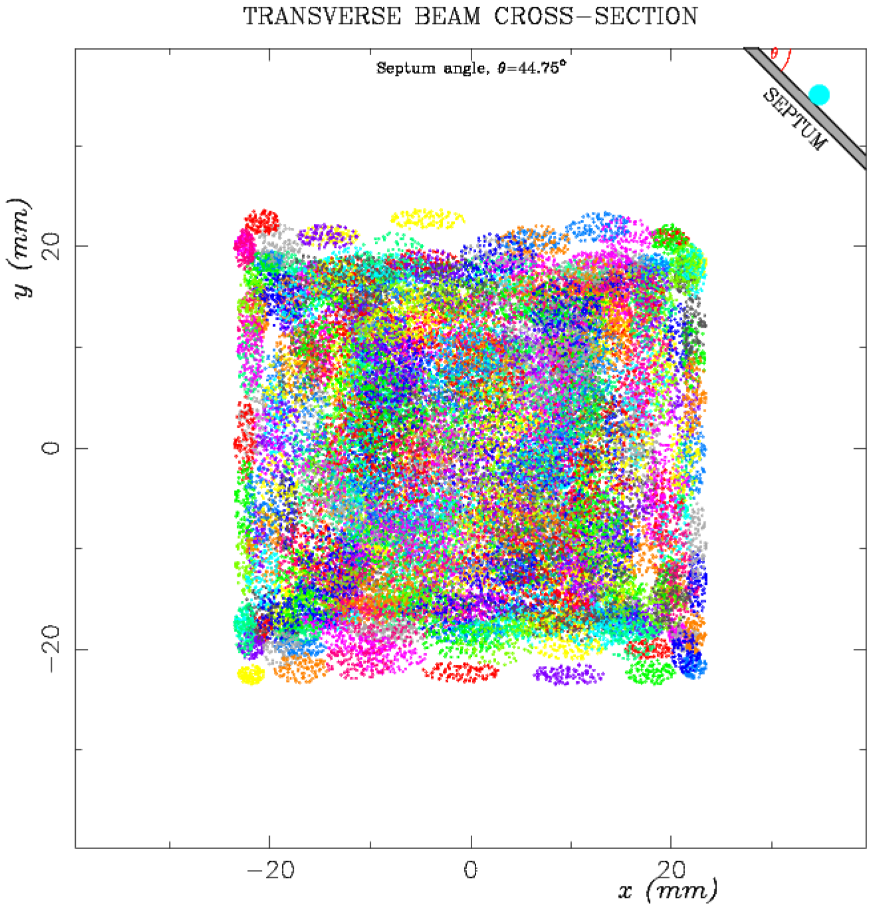
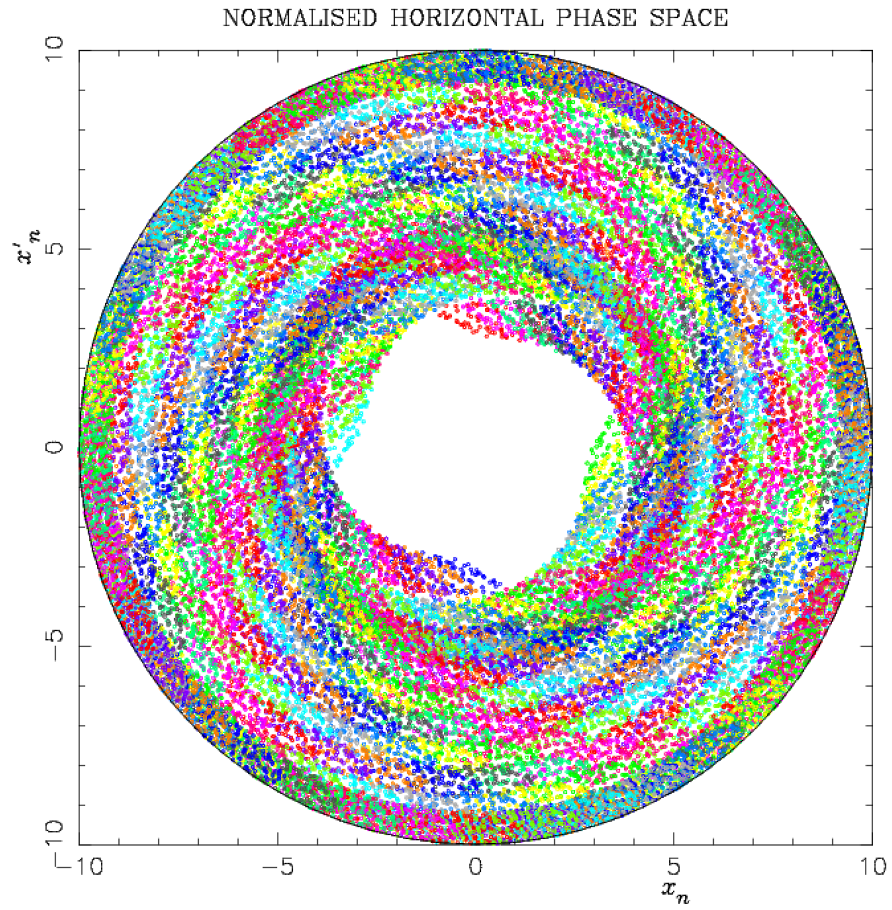
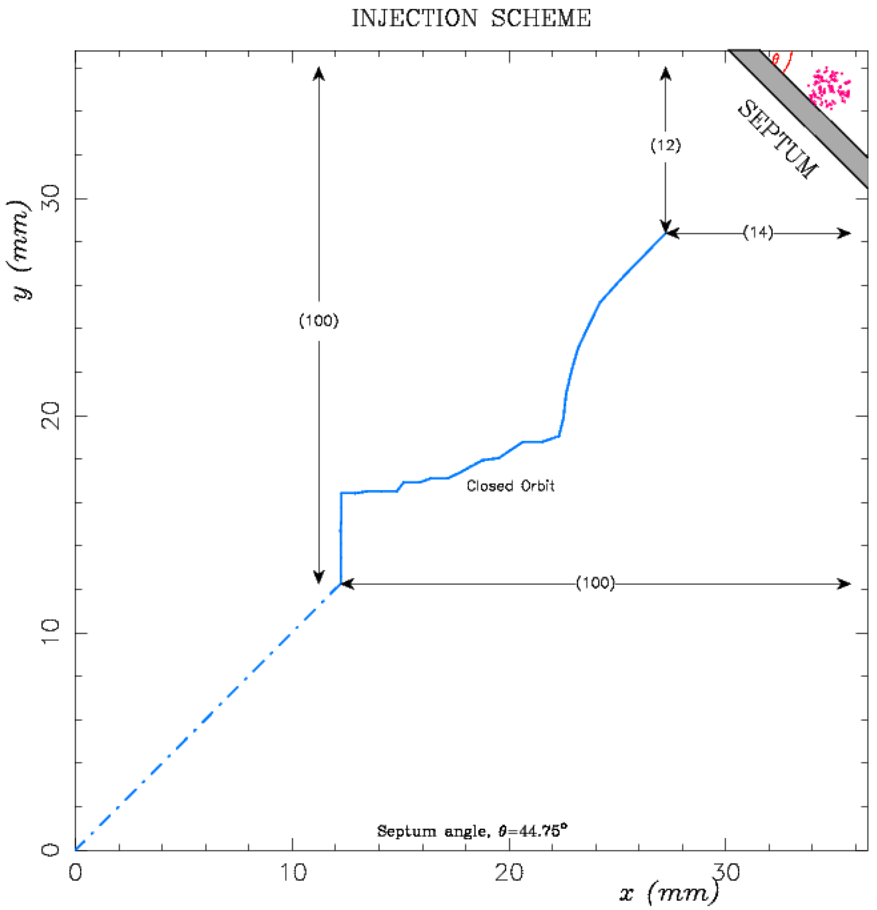
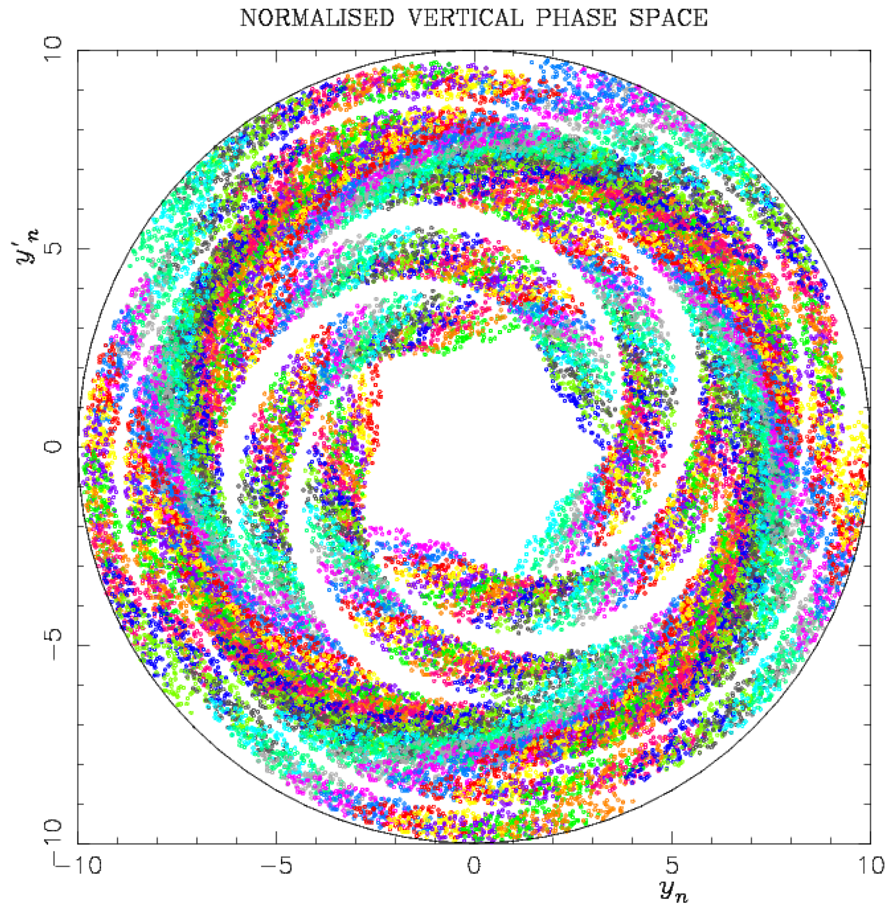
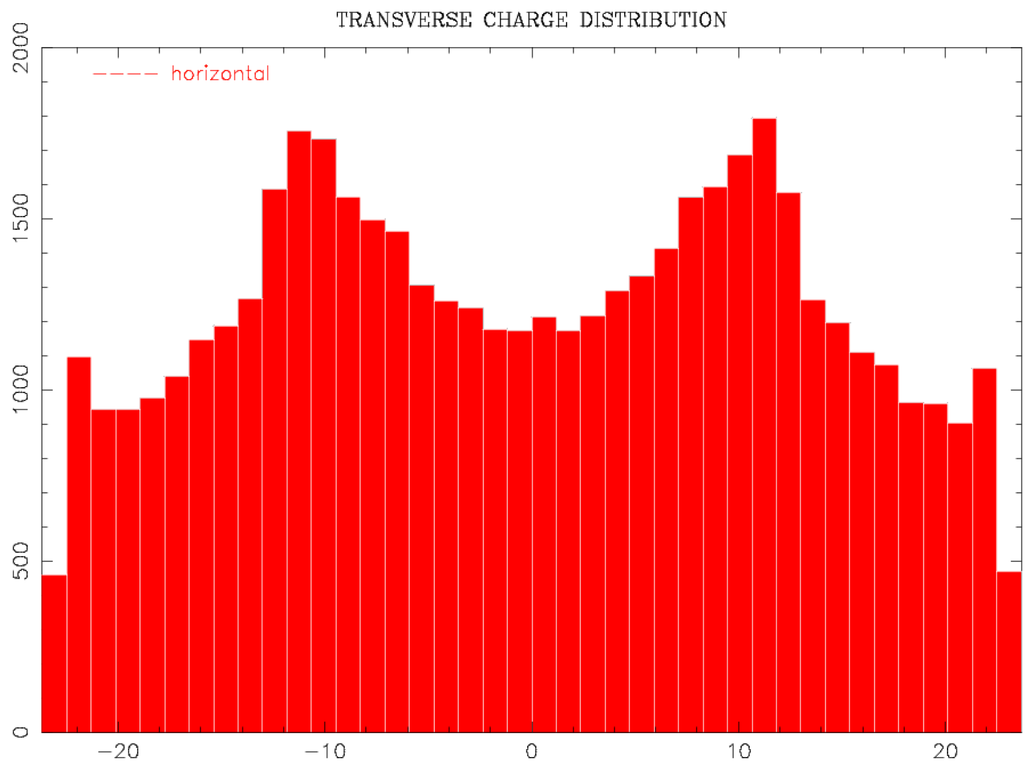
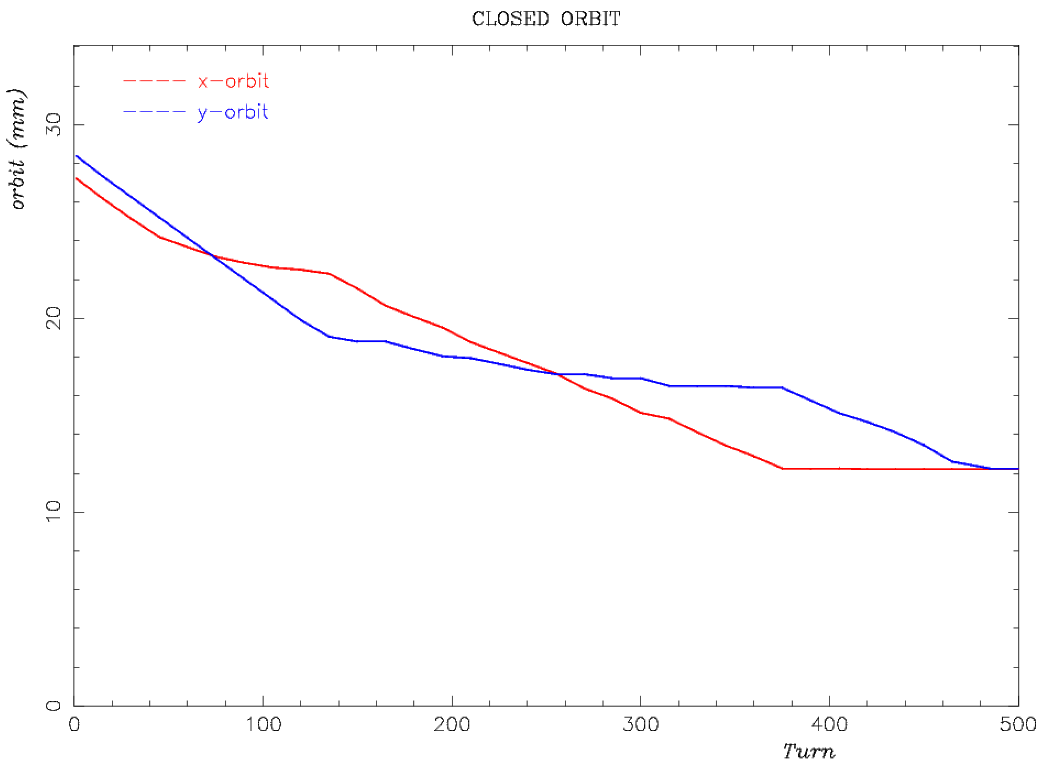

TRANSVERSE BEAM CROSS-SECTION
Septum angle, θ=44.75°
SEPTUM
y (mm)
x (mm)

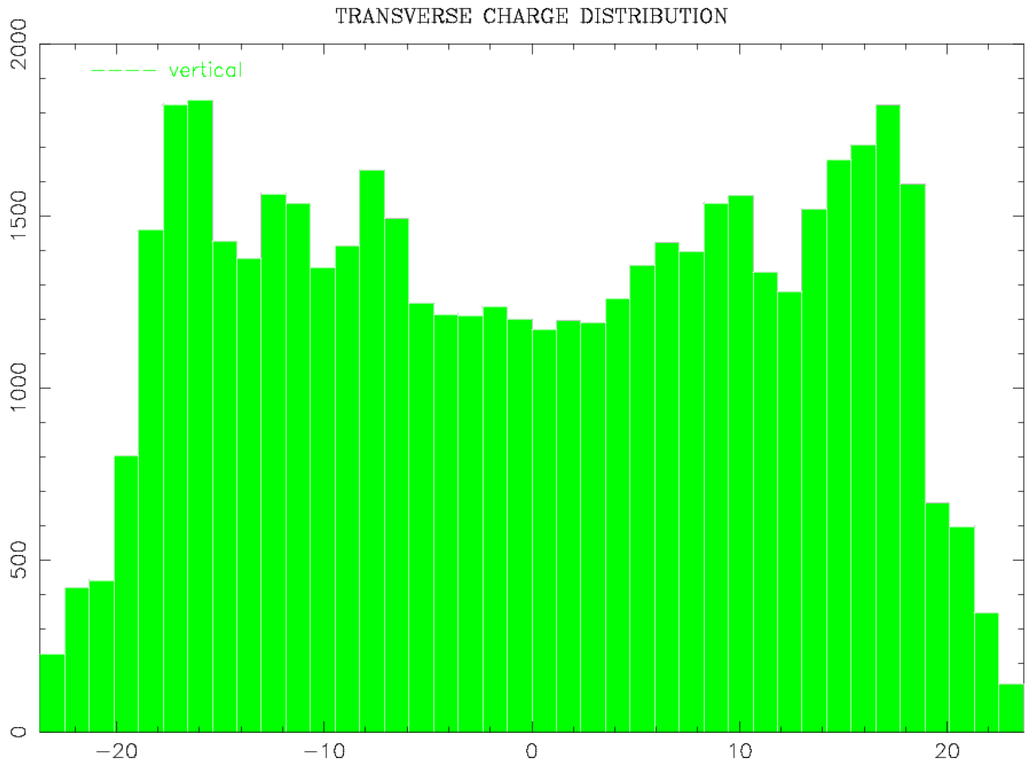

NORMALISED HORIZONTAL PHASE SPACE
x'n
xn

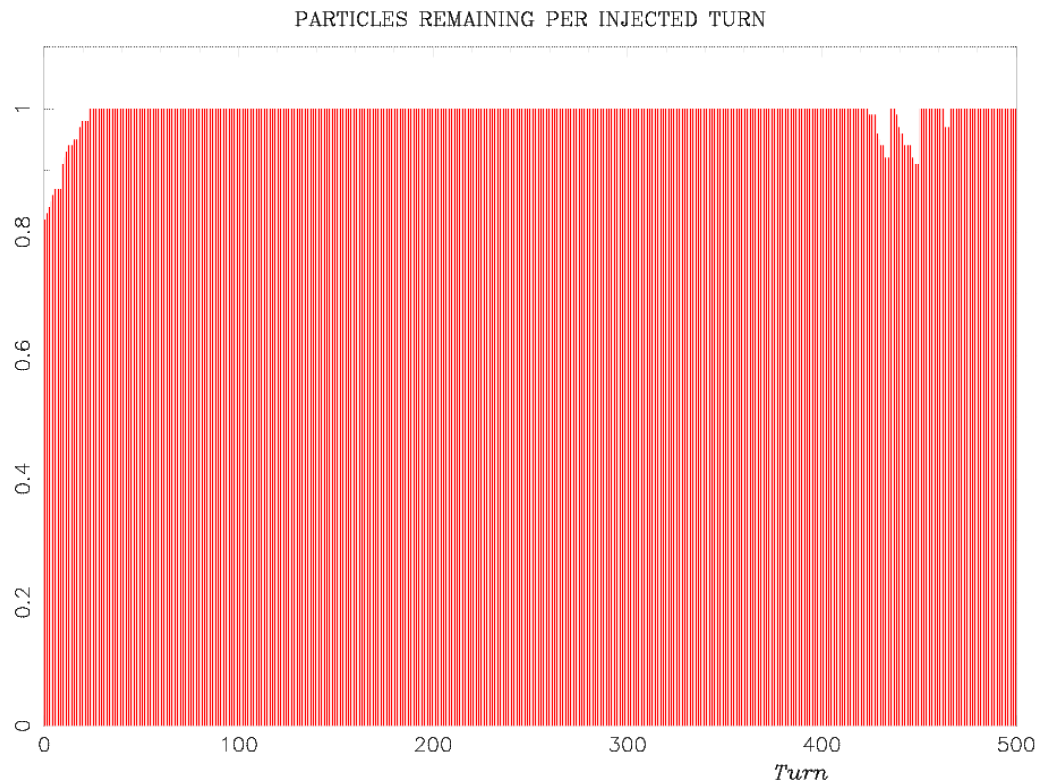

INJECTION SCHEME
SEPTUM
(12)
(14)
(100)
Closed Orbit
(100)
Septum angle, θ=44.75°
y (mm)
x (mm)


NORMALISED VERTICAL PHASE SPACE
y'n
yn









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Conclusion 1

- 500 turns with zero beam loss looks possible
- However, ring emittance of 100 π mm.mrad looks small. Cf. 300 π mm.mrad for SNS and ~400 π mm.mrad in ISIS
- Higher current proton sources are readily available (up to ~200 mA)
- So what could we do with 100 mA and 300 π mm.mrad?

Injection Parameters for 100 mA

Accumulated beam power (MW)	5.00
Linac beam current (mA)	100.00
Repetition rate (Hz)	14.0
Total number of particles ($\times 10^{14}$)	11.146
Injection interval required, Ne/I (ms)	1.79
Revolution period at injection, t (μs)	1.32
Ring circumference (m)	375.73
Number of injected turns	1350

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1500 Turn Model (5.55 MW)

REV	CLOSED ORBIT		INJECTED BEAM		MACHINE PARAMETERS				BEAM EMITTANCES	
	x	y	x	y	β_x	β_y	α_x	α_y	ϵ_x	ϵ_y
1	37.2083	37.6036	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	51.7754	49.2979
150	30.4583	34.8917	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	101.1682	66.3779
300	26.9703	30.6787	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	133.1499	98.2712
450	23.0223	28.6189	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	174.6423	116.1733
600	19.7906	27.0791	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	212.7880	130.5333
750	18.2672	24.5290	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	232.0749	156.1565
900	18.2672	20.6426	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	232.0749	199.6189
1050	18.2672	16.9552	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	232.0749	245.7842
1200	18.2672	13.4154	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	232.0749	294.6146
1350	15.9127	13.0437	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	263.5299	299.9976
1500	13.3526	13.0437	53.1741	53.3387	5.5480	5.6681	-0.5855	0.5944	300.0000	299.9976

Total beam loss =0.00 %
(assuming uniform beam)

EQUATION OF SEPTUM $ax + by + c = 0$, with

$a = 0.789315, b = 0.613989, c = -72.757873$ (x and y in mm)

Septum angle $\theta = 52.12°$

Ring acceptance $\mathcal{A} = 480\,\pi$ mm.mrad

Space charge tune depression $\left(\propto \frac{N}{\epsilon}\right) = 0.033$

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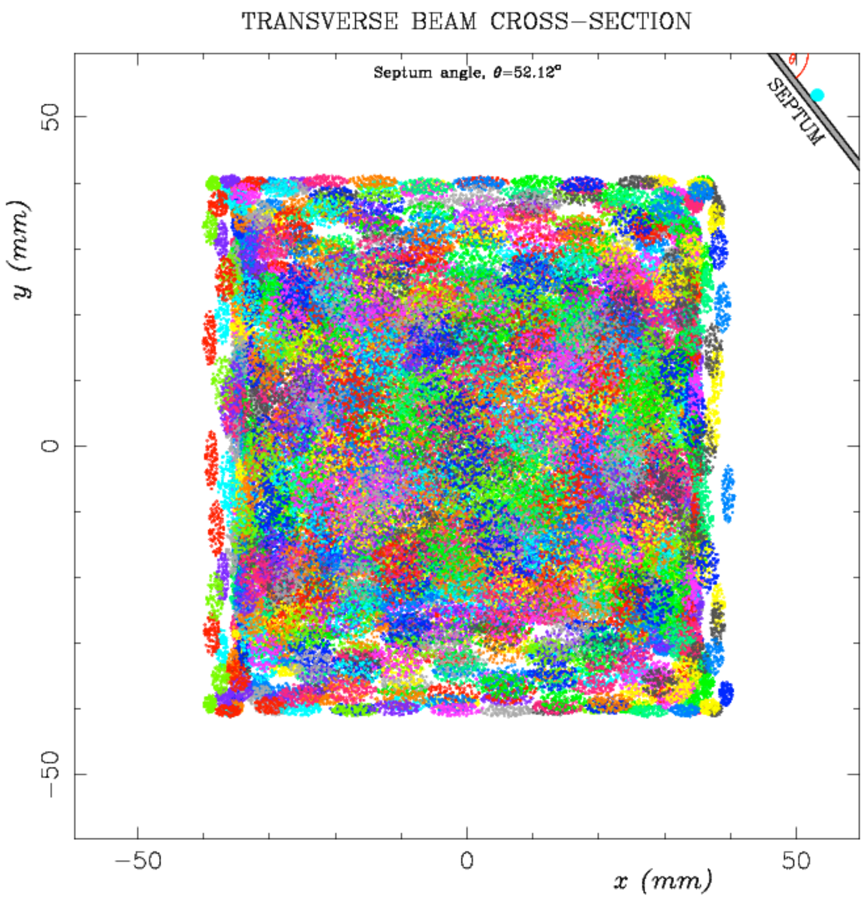
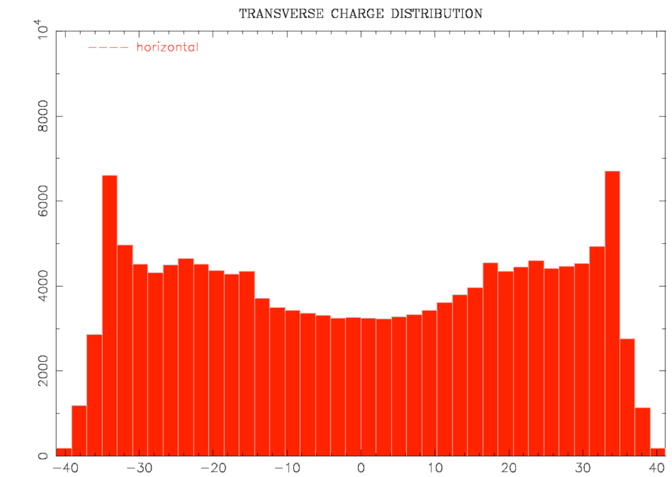
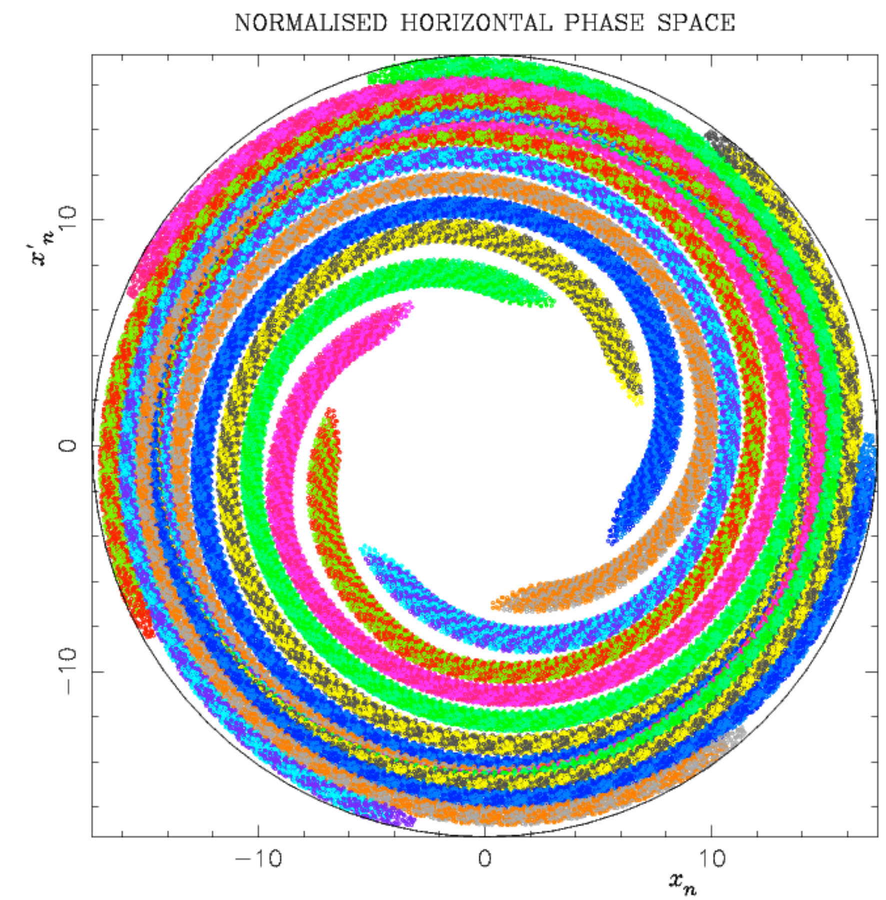
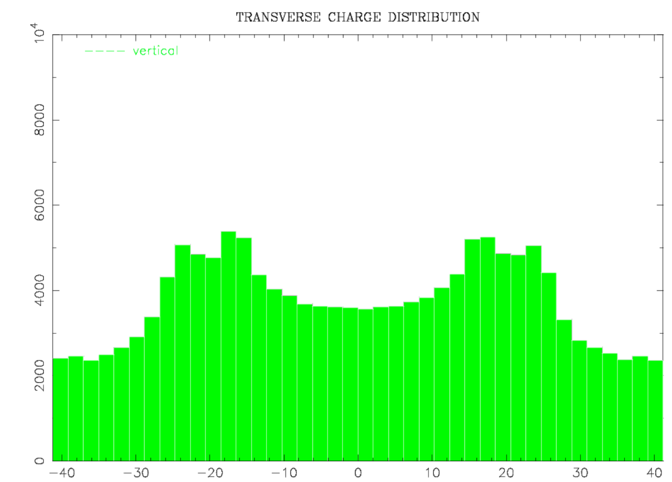
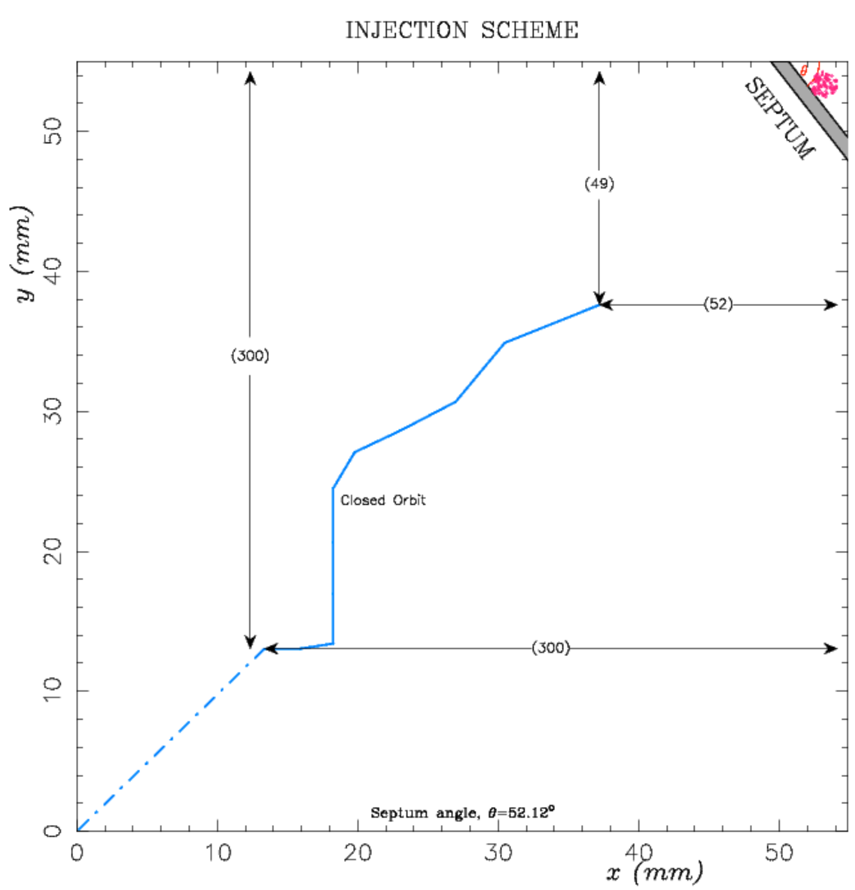
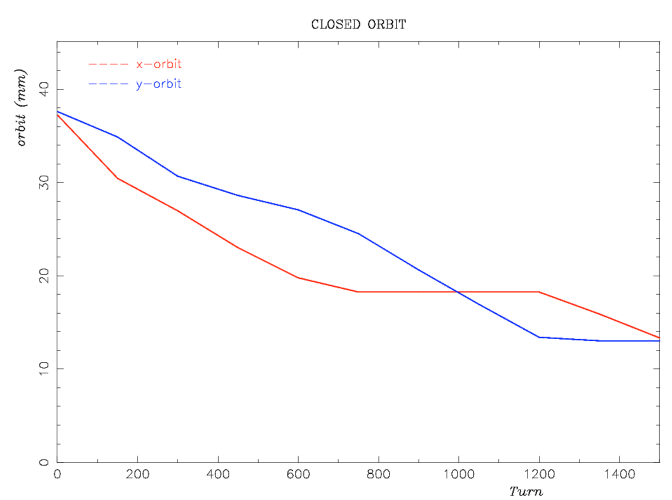

TRANSVERSE BEAM CROSS-SECTION
Septum angle, θ=52.12°
SEPTUM
y (mm)
x (mm)

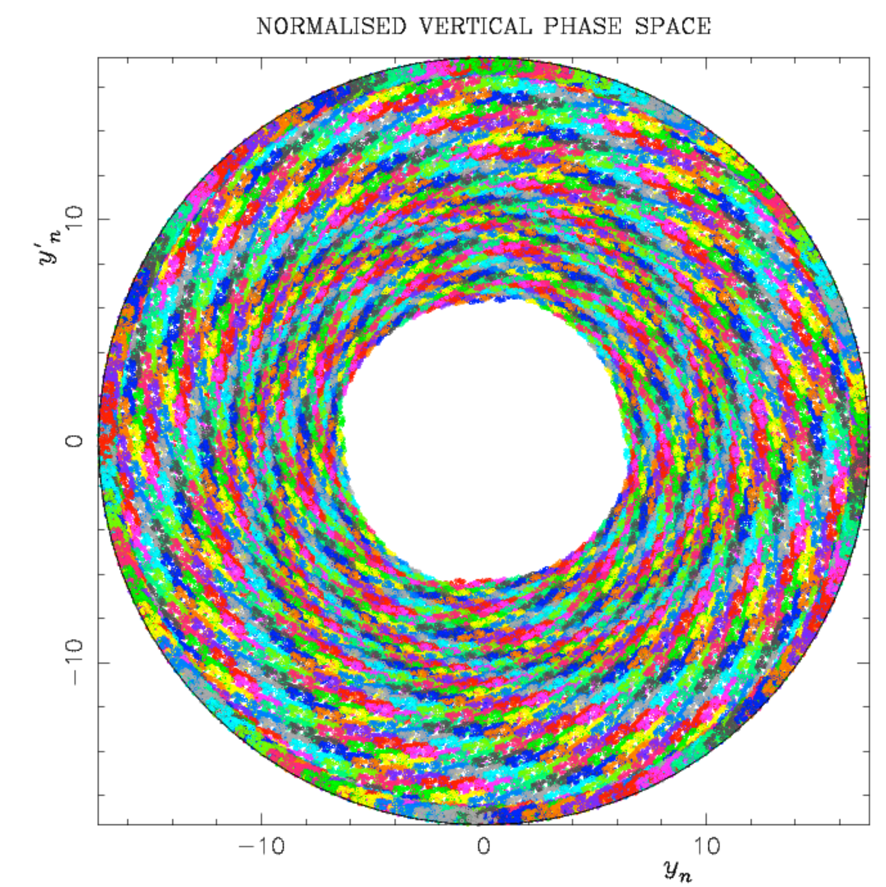

TRANSVERSE CHARGE DISTRIBUTION
horizontal


NORMALISED HORIZONTAL PHASE SPACE
x'n
xn


TRANSVERSE CHARGE DISTRIBUTION
vertical


INJECTION SCHEME
SEPTUM
(300)
(49)
(52)
Closed Orbit
(300)
Septum angle, θ=52.12°
y (mm)
x (mm)


CLOSED ORBIT
x-orbit
y-orbit
orbit (mm)
Turn


NORMALISED VERTICAL PHASE SPACE
y'n
yn