Ring Injection for High Intensity Accelerators

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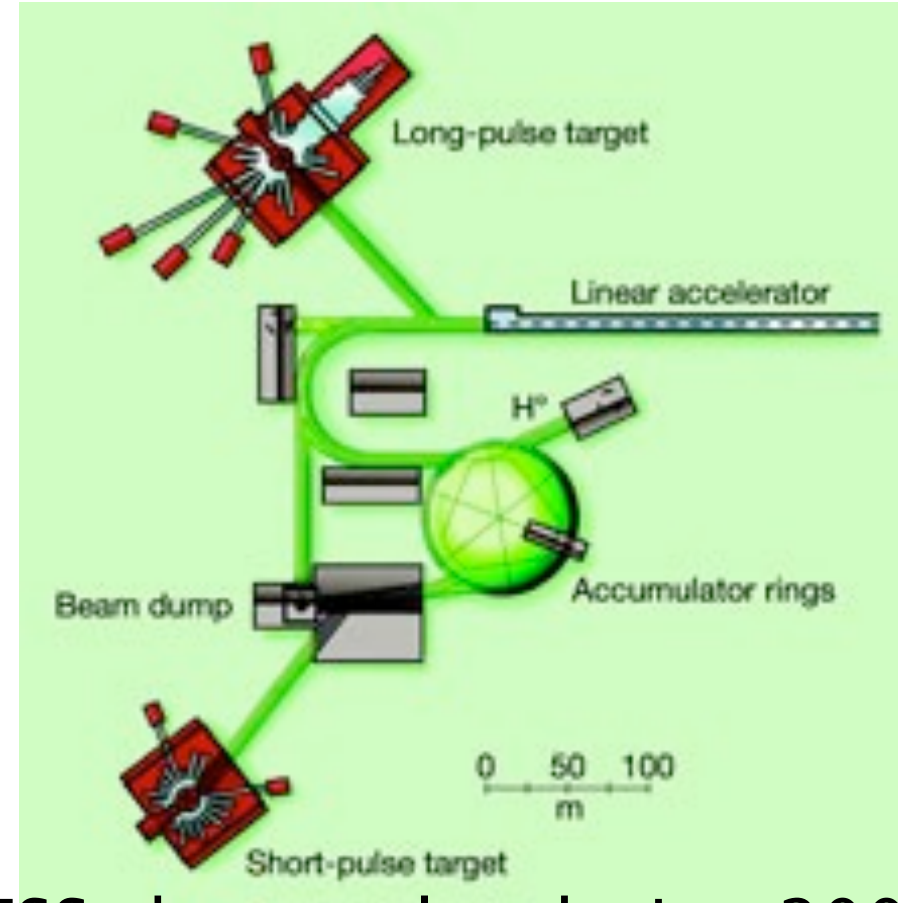
High Intensity Accelerators


ISIS Spallation Source, RAL

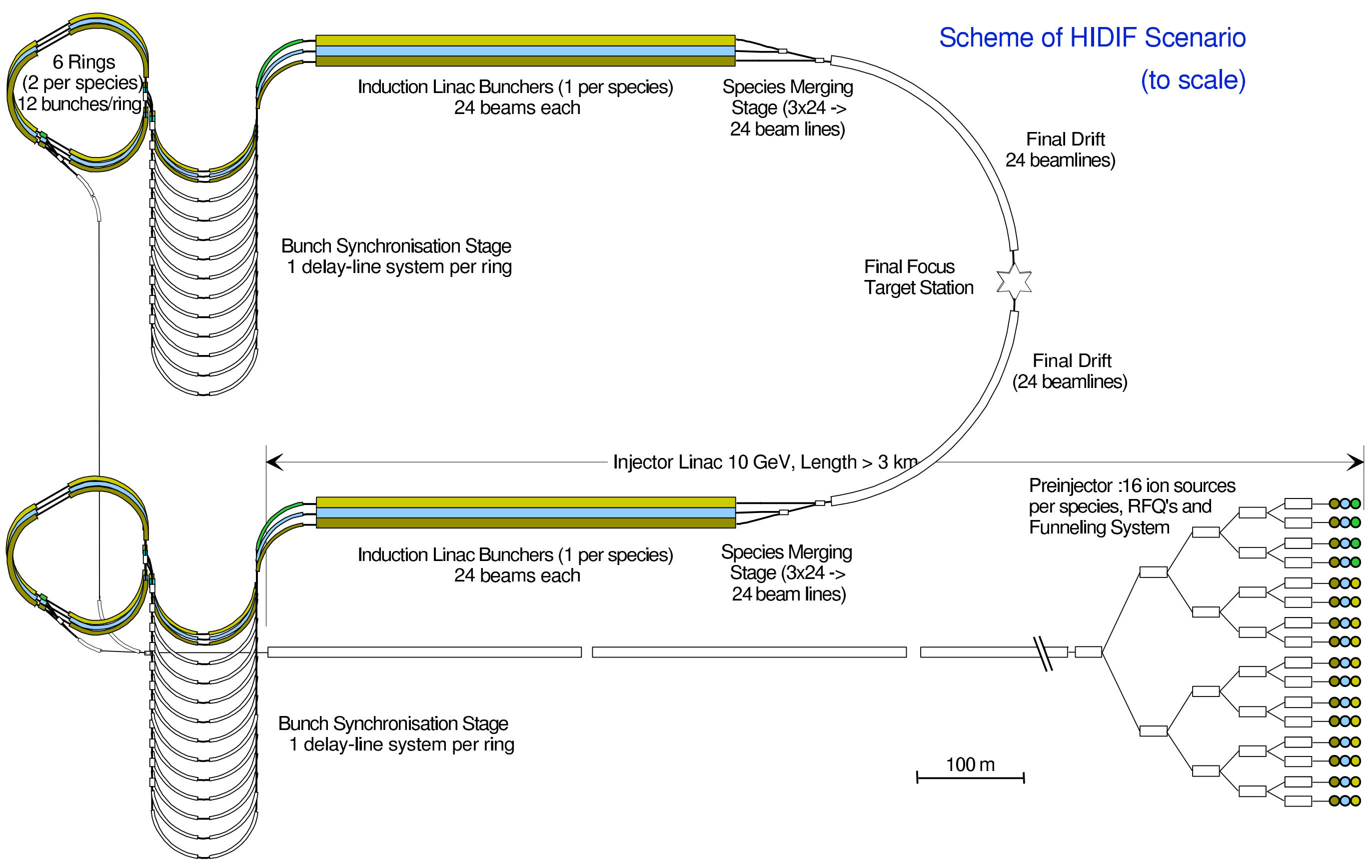
SNS, Oak Ridge, TN


J-PARC, Tokai-mura, Japan

Chinese Spallation Source, Dongguan



ESS short-pulse design 2002



HIDIF Accelerators for Inertial Confinement Fusion

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Beam Power

The mean beam power is given by $\mathcal{P} = Ne\mathcal{E}f$ where

- N is the total number of particles
- $\mathcal{E}$ is the (mean) energy of the beam (eV)
- f is the repetition rate (Hz)

Machine	$N(\times 10^{12})$	$\mathcal{E}$ (GeV)	f (Hz)	$\mathcal{P}$ (MW)
SNS (ORNL)	146	1.0	60	1.4
ISIS (RAL)	25	0.8	50	0.16
ESS (short-pulse)	468	1.334	50	5.0
Neutrino Factory	50	10	50	4.0

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Linac current $\quad I_L = N_b e f_L,$

N_b = number of particles in each linac micro-bunch entering ring at a rate f_L per second.

Injection period $\quad \tau_{inj} \qquad \Longrightarrow \qquad N_b f_L \tau_{inj} = N$

$$\Longrightarrow \qquad \tau_{inj} = \frac{N}{N_b f_L} = \frac{eN}{I_L}$$

Ring revolution period $\quad \tau = \dfrac{2\pi R}{\beta c}$

$$\Longrightarrow \qquad \text{number of injection revolutions (turns)} = \frac{\tau_{inj}}{\tau} = \frac{Ne}{I_L}\frac{\beta c}{2\pi R}$$

Machine	I_L (mA)	T_{inj} (MeV)	β	R (m)	τ_{inj} (μs)	Turns
SNS	25	1000	0.875	35	940	1100
ISIS	$\lesssim$20	70	0.367	26	200	150-200
ESS	114	1334	0.91	35	470	583
NF	50	180	0.544	32.5	200	160

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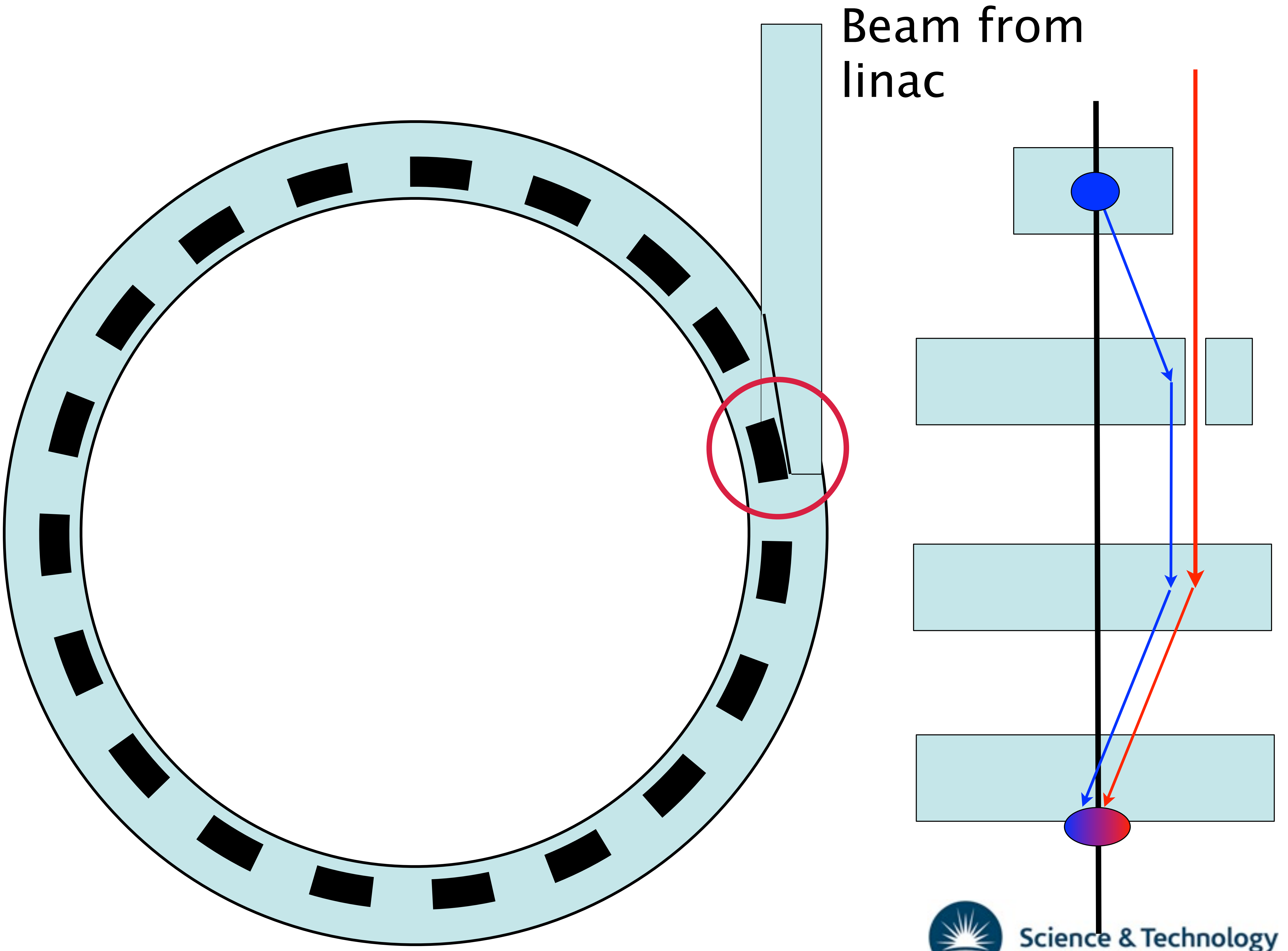
Beam from
linac

Liouville’s Theorem

In the local region of a particle, the particle density in phase space is constant, provided that the particles move in a general field consisting of magnetic fields and of fields whose forces are independent of velocity.

$$\frac{\partial f}{\partial t} + (\nabla f) \cdot \mathbf{v} + (\nabla_p f) \cdot \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \frac{\mathrm{d}f}{\mathrm{d}t} = 0$$

Equivalent to conservation of total number of particles.
Ignores effects of radiation; does not hold for dissipative systems.

Liouville’s theorem can be circumvented by use of dissipative forces e.g. synchrotron radiation, ionisation cooling, stochastic cooling. Special case is to strip an H^- beam with a foil and merge it with a proton beam. The interaction with the foil is the “dissipative force”.

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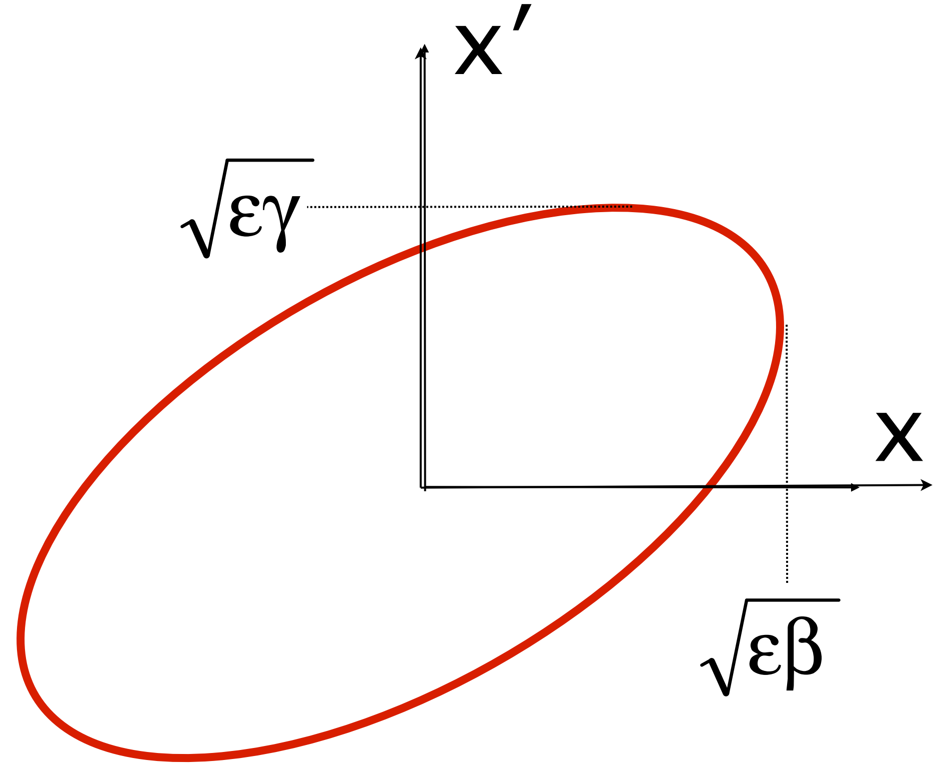
Normalised Phase Space

$$\eta = \frac{x}{\sqrt{\beta}}, \qquad \eta' = \sqrt{\beta}\left(x' + \frac{\alpha}{\beta}x\right)$$

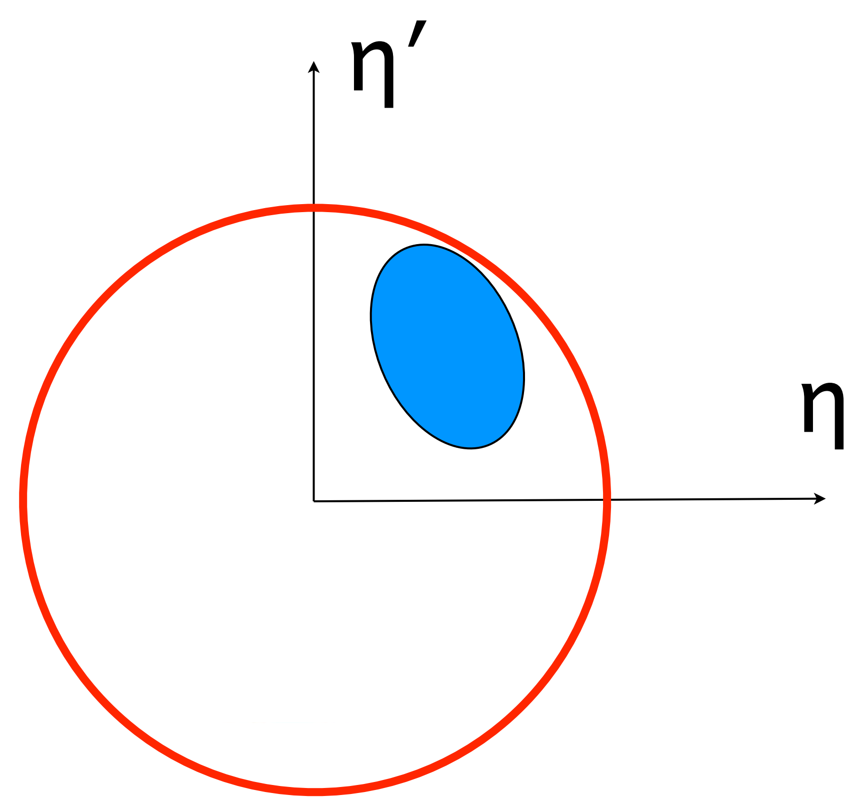


Ring phase at injection point

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 \leq \epsilon$$

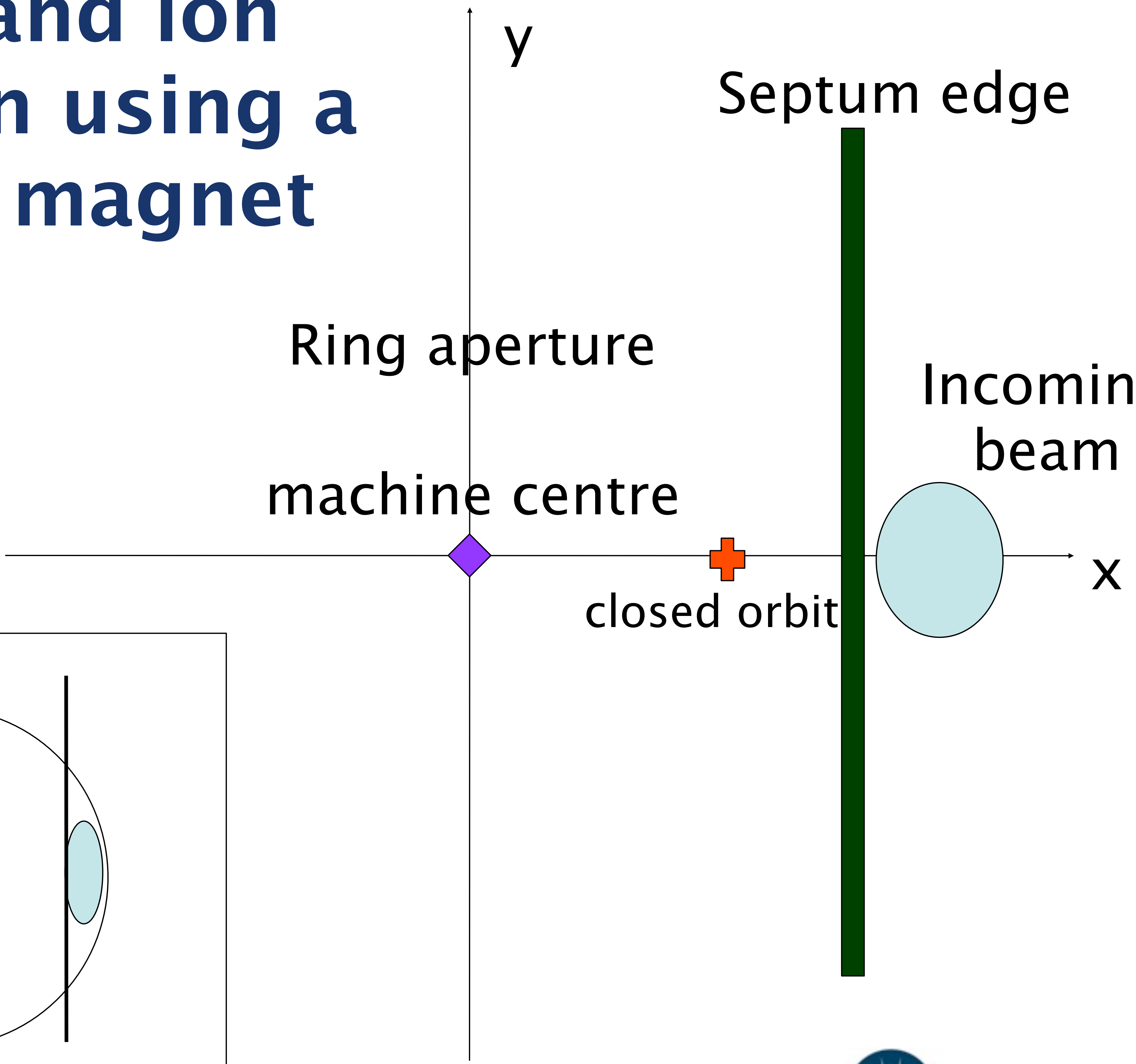
becomes

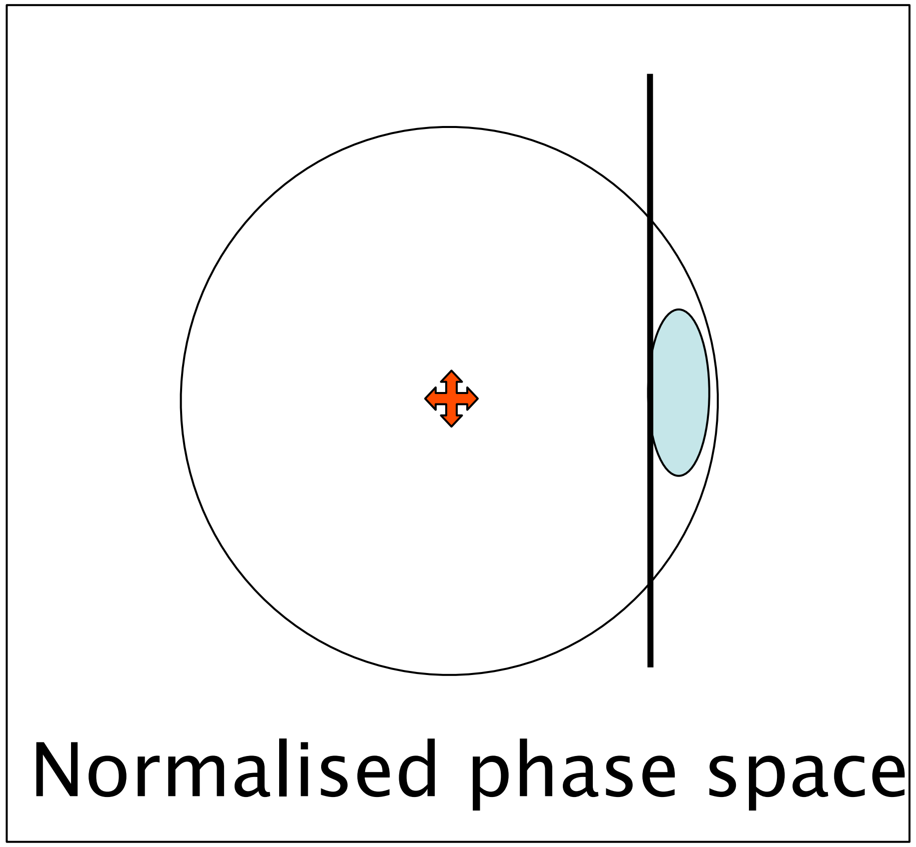
$$\eta^2 + \eta'^2 \leq \epsilon$$

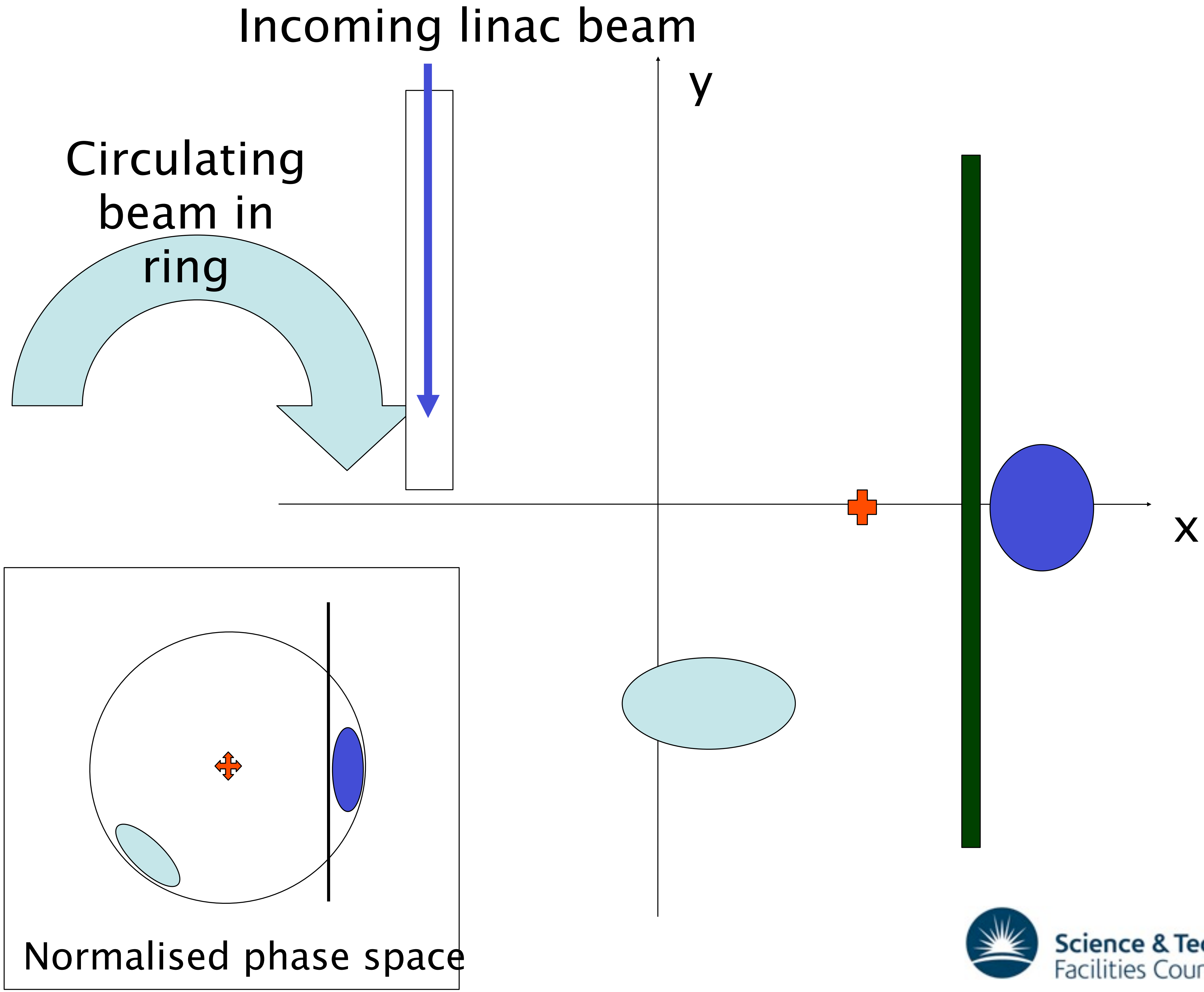


Injection turns rotate at constant radius through an angle given by the machine per tune per revolution.

Proton and ion injection using a septum magnet







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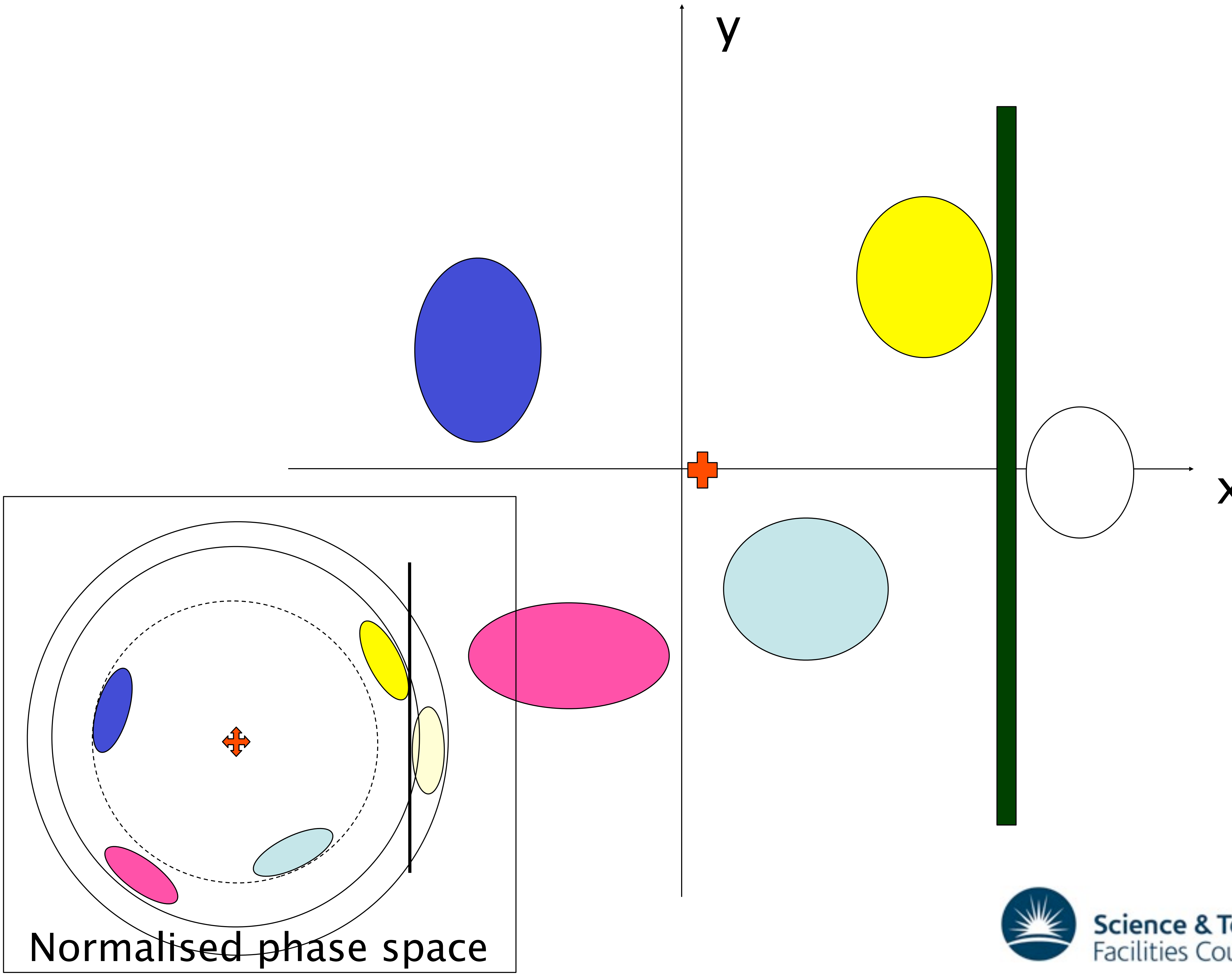
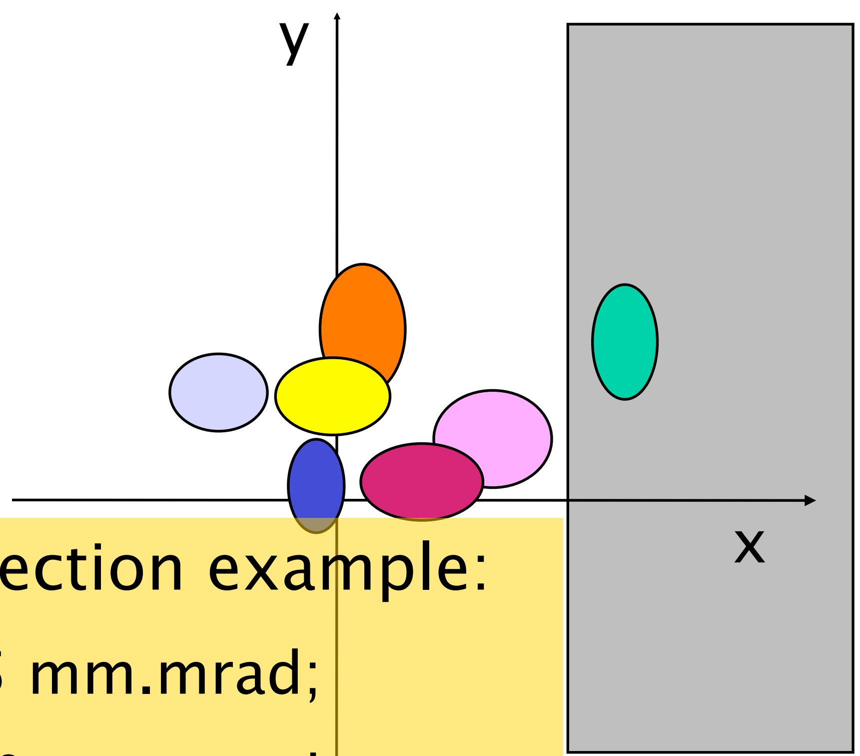

y
x
Normalised phase space

Proton/ion Injection

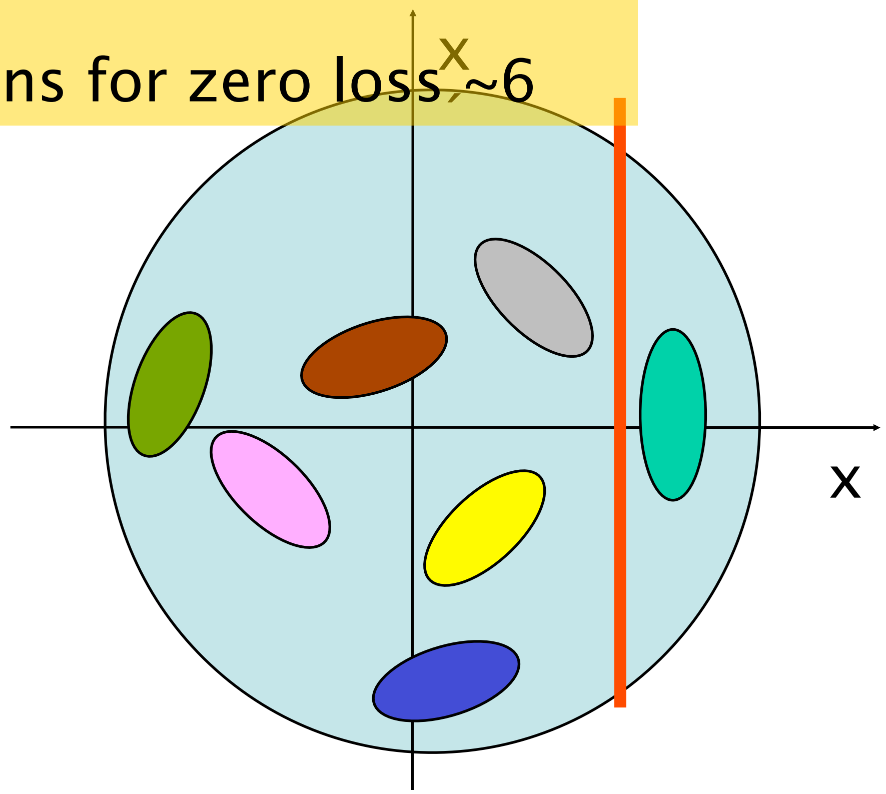


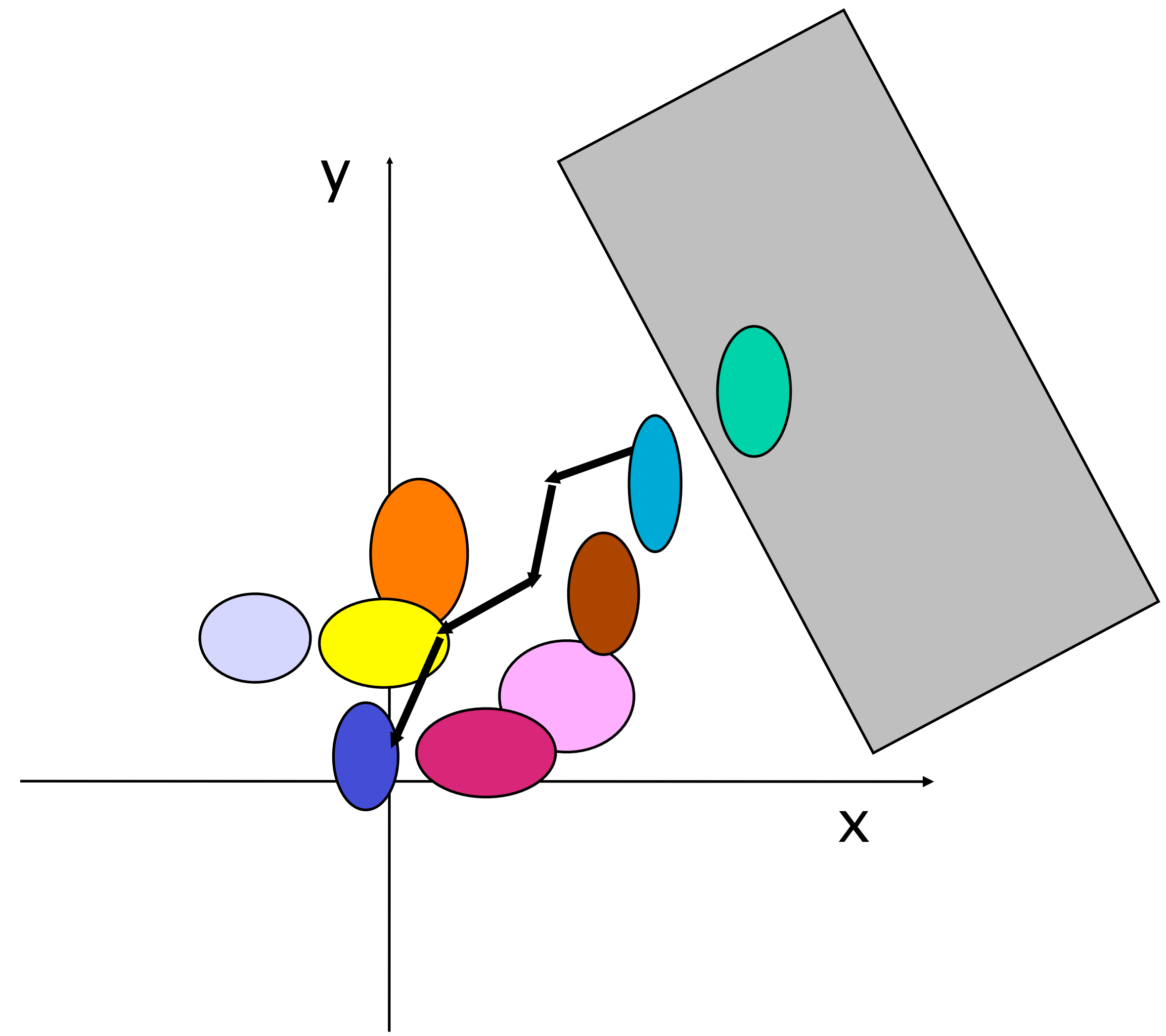
Single plane injection example:

linac emittance 5 mm.mrad;

ring emittance 50 mm.mrad.

Number of turns for zero loss ~6





Two plane injection with tilted septum

e.g. linac emittance 4 mm.mrad;

ring emittance 50 mm.mrad

Number of turns for zero loss ~22

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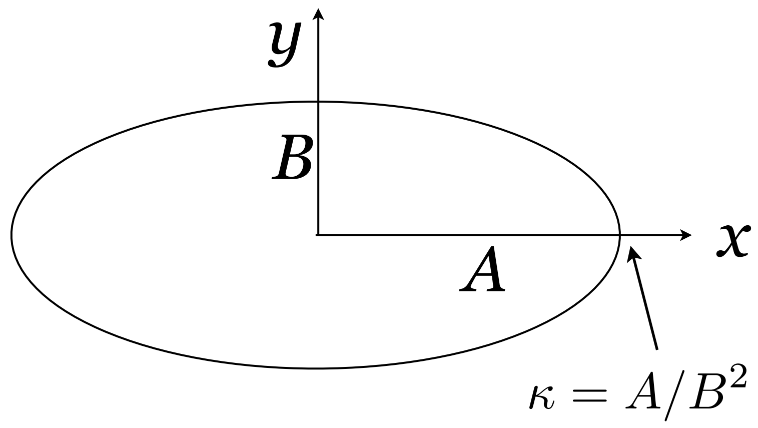
Optimal Conditions for Injection

For a general upright ellipse $\dfrac{x^2}{A^2} + \dfrac{y^2}{B^2} = 1$, curvature at the end of the x-axis is:



$$\frac{\frac{\mathrm{d}^2 y}{\mathrm{d}x^2}}{\left(1+\left(\frac{\mathrm{d}y}{\mathrm{d}x}\right)\right)^{\frac{3}{2}}} = \frac{A}{B^2}$$

Normalised coordinates: $\eta = \dfrac{x}{\sqrt{\beta}}, \quad \eta' = \sqrt{\beta}\left(x' + \dfrac{\alpha}{\beta}x\right)$

$$\implies \quad x = \eta\sqrt{\beta}, \quad x' = \frac{1}{\sqrt{\beta}}(\eta' - \alpha\eta)$$

Ring phase space: $\gamma x^2 + 2\alpha x x' + \beta x'^2 = \epsilon \ \rightarrow \ \eta^2 + \eta'^2 = \epsilon$

$\implies$ curvature $\kappa = \dfrac{1}{\sqrt{\epsilon}}$

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Injected turn phase-space:

$$\gamma_i x^2 + 2\alpha_i x x' + \beta_i x'^2 = \epsilon_i$$

$$\implies \qquad \gamma_i \beta \eta^2 + 2\alpha_i \eta(\eta' - \alpha\eta) + \frac{\beta_i}{\beta}(\eta' - \alpha\eta)^2 = \epsilon_i$$

$$\implies \qquad \eta^2 \left(\beta\gamma_i + \alpha^2 \frac{\beta_i}{\beta} - 2\alpha\alpha_i\right) + 2\eta\eta' \left(\frac{\alpha_i}{\beta_i} - \frac{\alpha}{\beta}\right) + \frac{\beta_i}{\beta}\eta'^2 = \epsilon_i$$

Make $\dfrac{\alpha_i}{\beta_i} = \dfrac{\alpha}{\beta}$ so ellipse is upright. Then

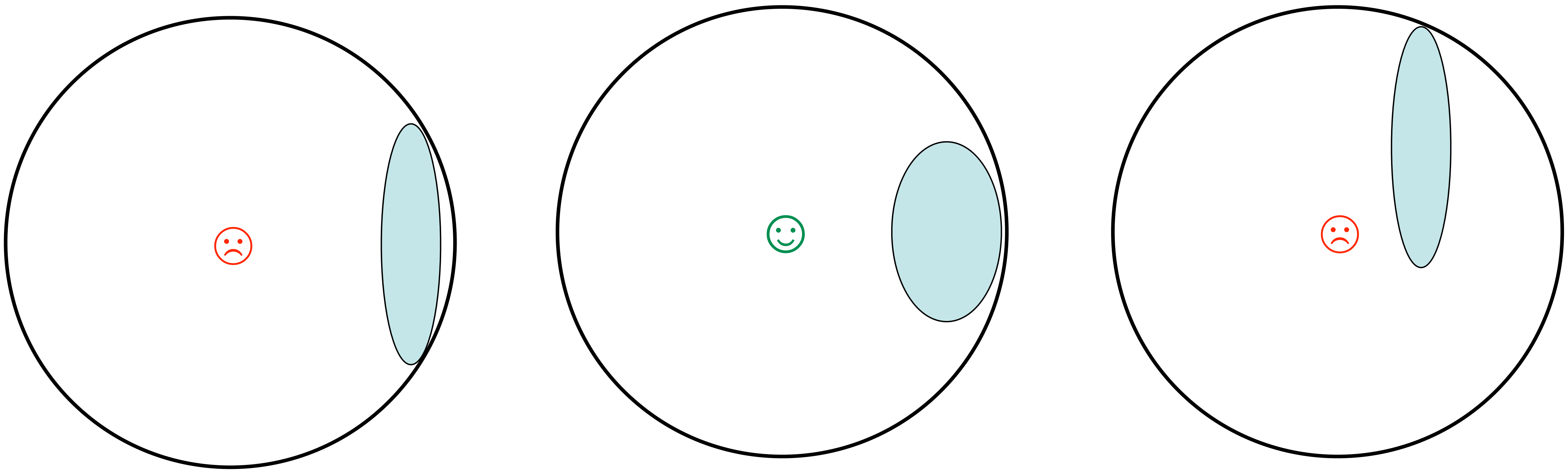
$$\beta\gamma_i + \alpha^2 \frac{\beta_i}{\beta} - 2\alpha\alpha_i = \beta\gamma_i - \alpha^2 \frac{\beta_i}{\beta} = \frac{\beta}{\beta_i}\left(\beta_i\gamma_i - \left(\alpha\frac{\beta_i}{\beta}\right)^2\right)$$

$$= \frac{\beta}{\beta_i}(\beta_i\gamma_i - \alpha_i^2) = \frac{\beta}{\beta_i}$$

Injected turn is $\dfrac{\beta}{\beta_i}\eta^2 + \dfrac{\beta_i}{\beta}\eta'^2 = \epsilon_i \implies$ curvature $\boxed{\kappa_i = \left(\dfrac{\beta_i}{\beta}\right)^{\frac{3}{2}} \dfrac{1}{\sqrt{\epsilon_i}}}$

Curvature of ring phase space is $\kappa = \frac{1}{\sqrt{\epsilon}}$

Curvature of incoming turn is $\kappa_i = \left(\frac{\beta_i}{\beta}\right)^{\frac{3}{2}} \frac{1}{\sqrt{\epsilon_i}}$



Want $\kappa_i > \kappa$ or $\frac{\beta_i}{\beta} \geqslant \left(\frac{\epsilon_i}{\epsilon}\right)^{\frac{1}{3}}$

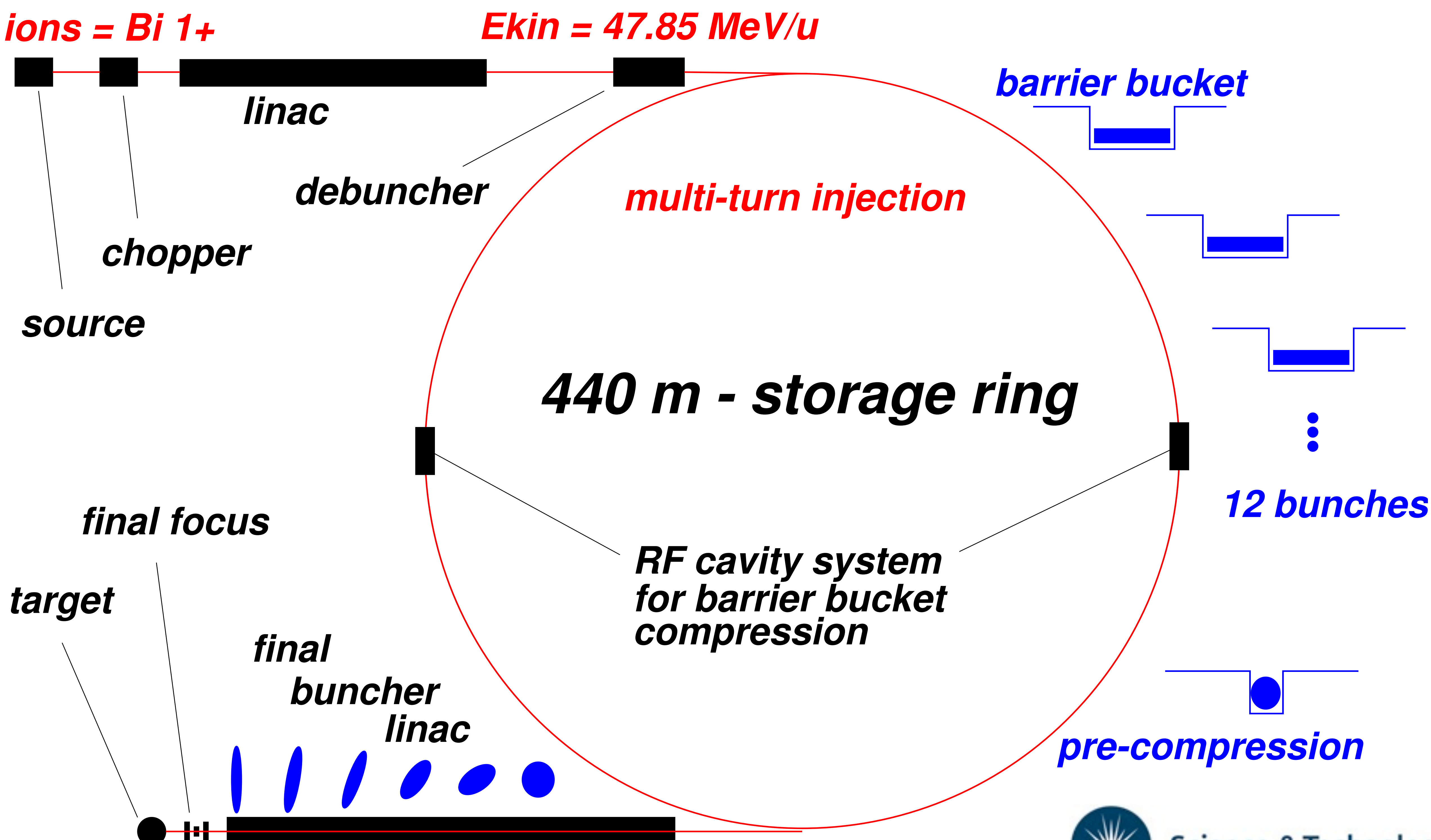
(x_i, x_i') centre of injected turn
(x_o, x_o') closed orbit

Conditions for optimum injection into phase space:

$$\frac{\alpha_i}{\beta_i} = \frac{\alpha}{\beta} = -\frac{x_i' - x_o'}{x_i - x_o}$$

$$\frac{\beta_i}{\beta} \geq \left(\frac{\epsilon_i}{\epsilon}\right)^{\frac{1}{3}}$$

Multiturn Injection in HIDIF



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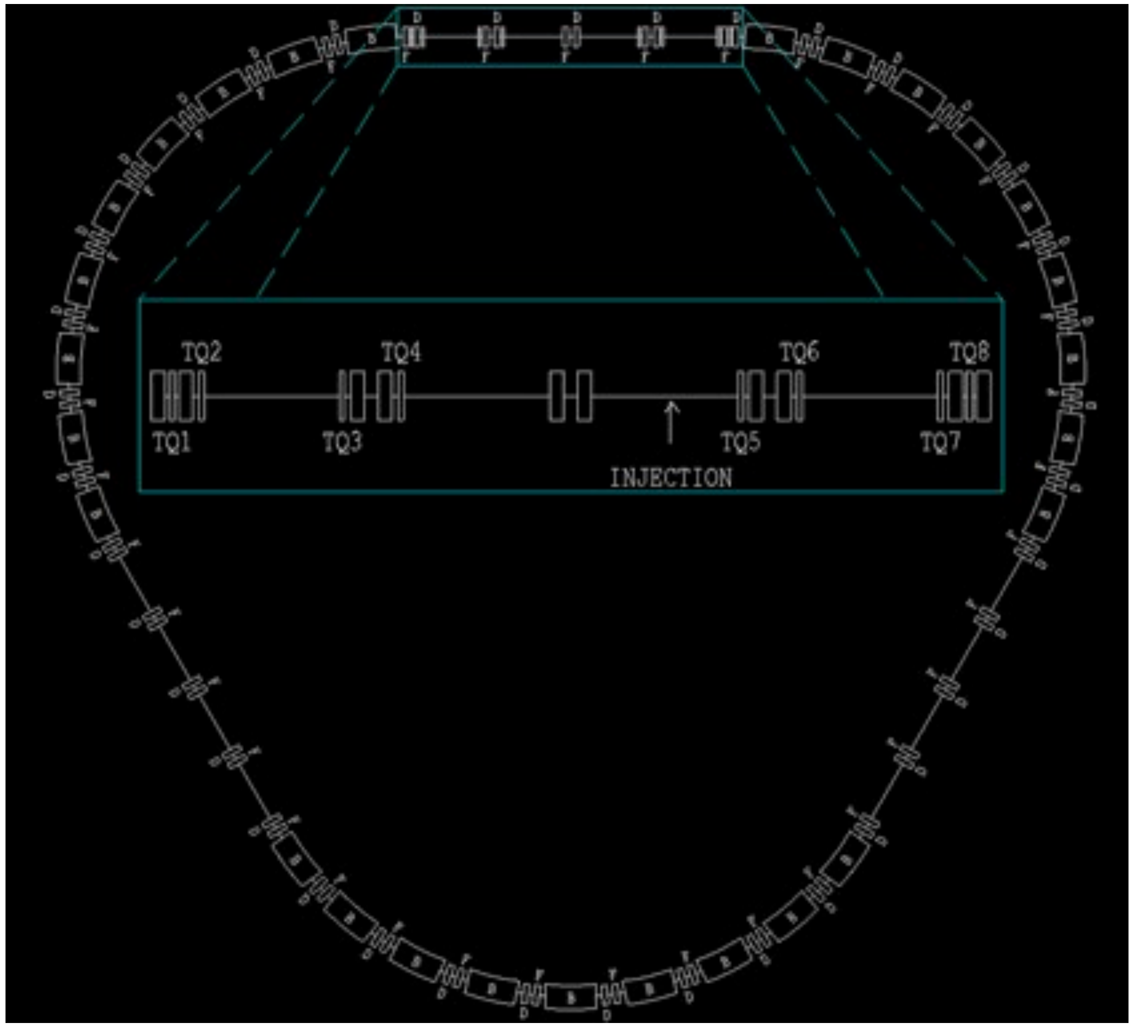
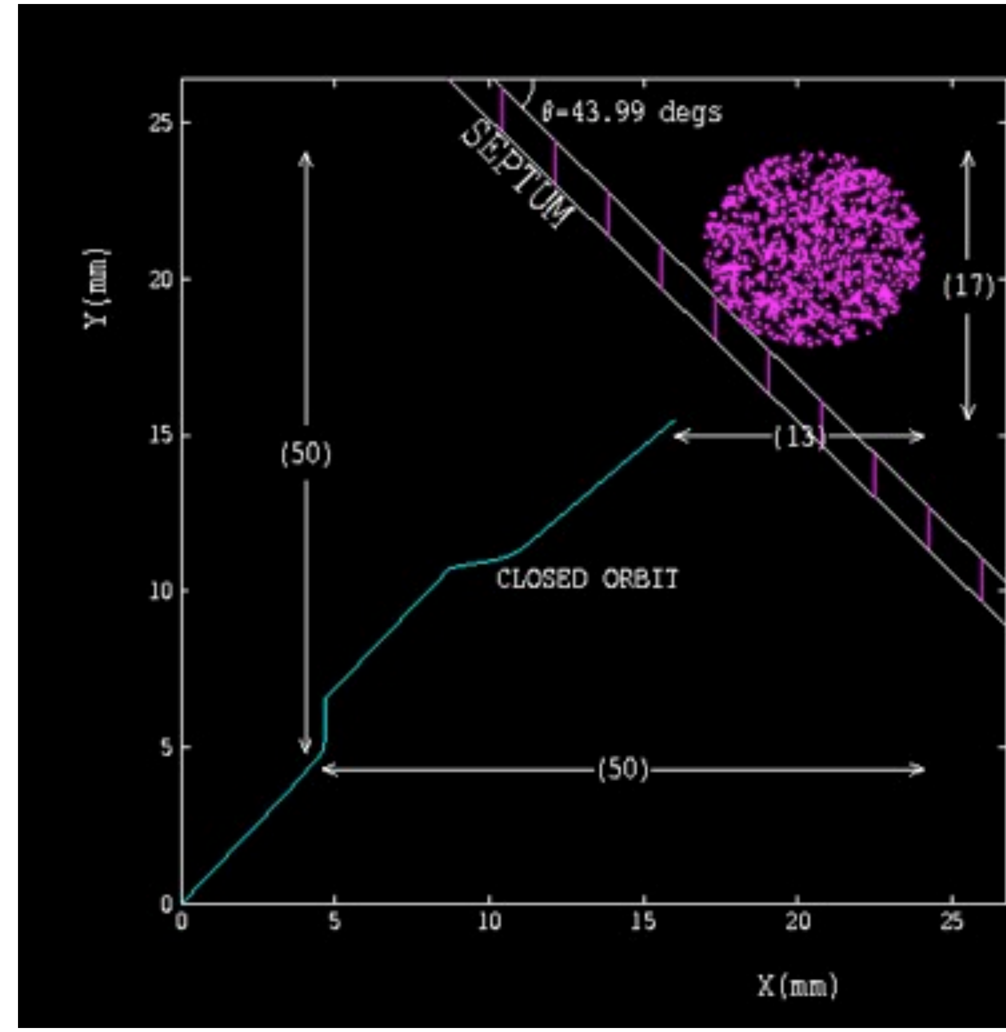
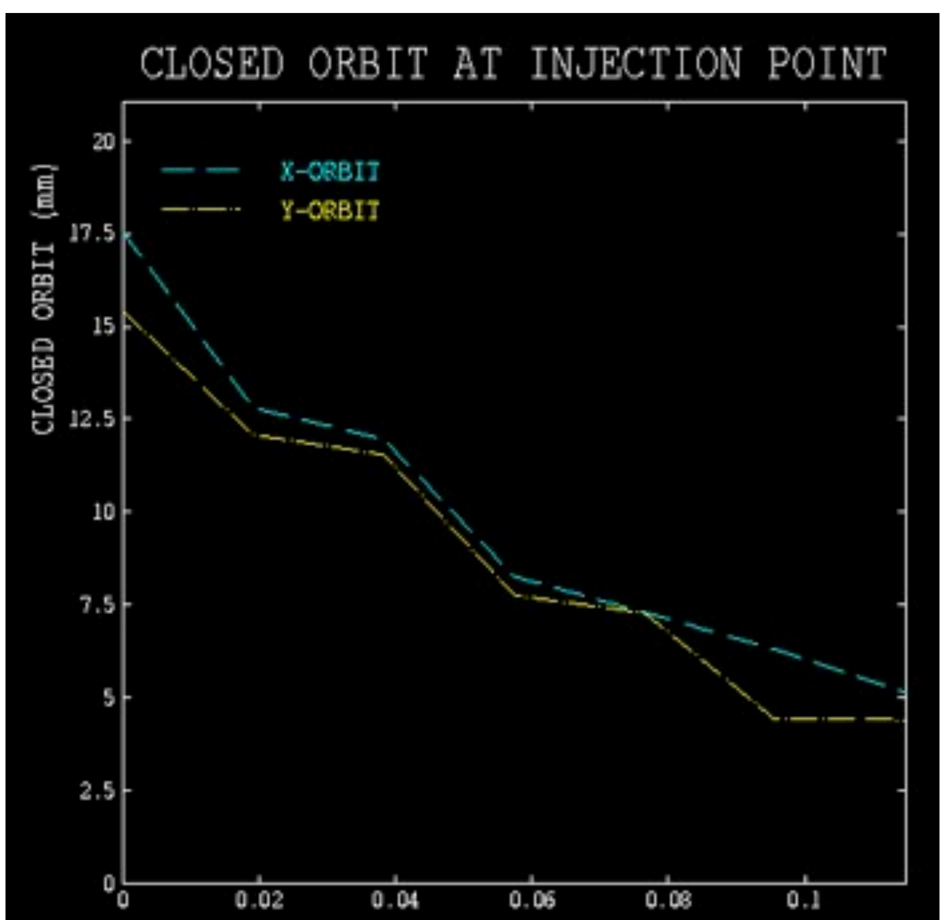
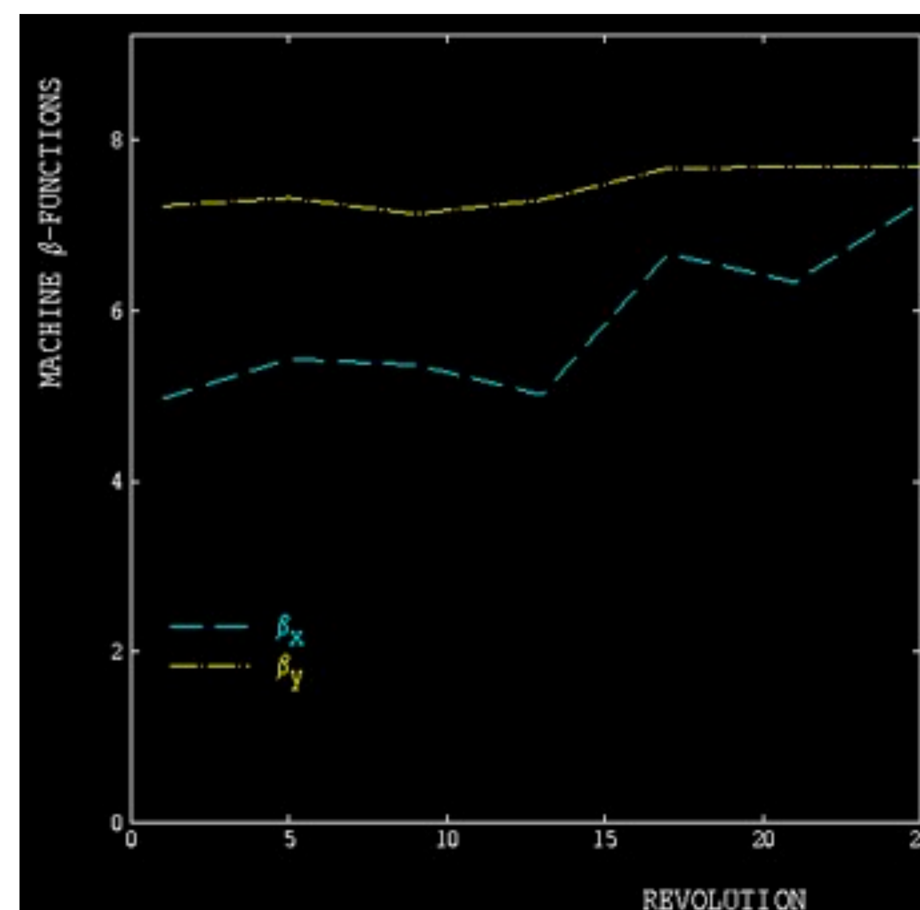




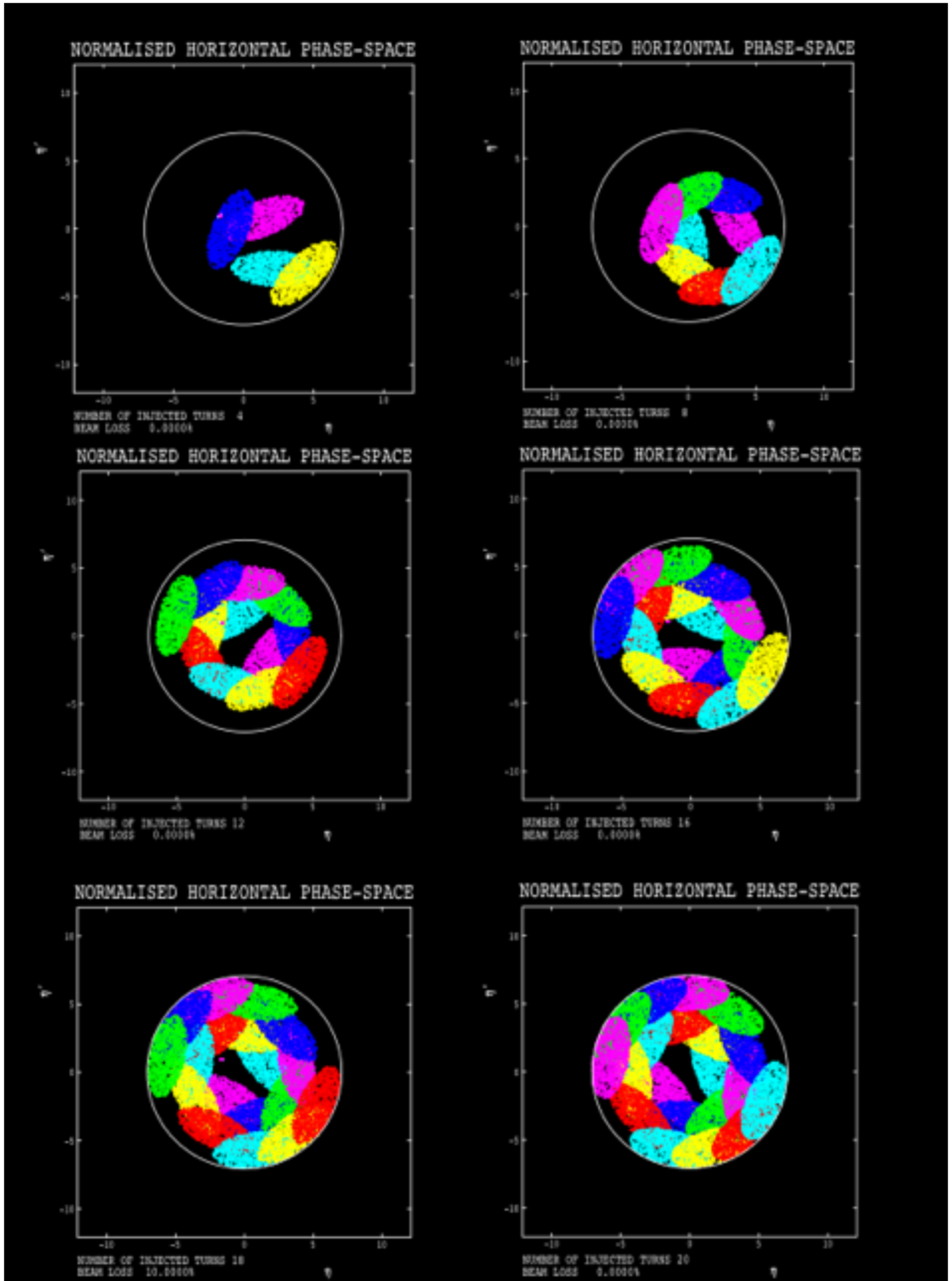
Simultaneous injection of Bi^{+1} into H and V phase spaces using tilted septum.



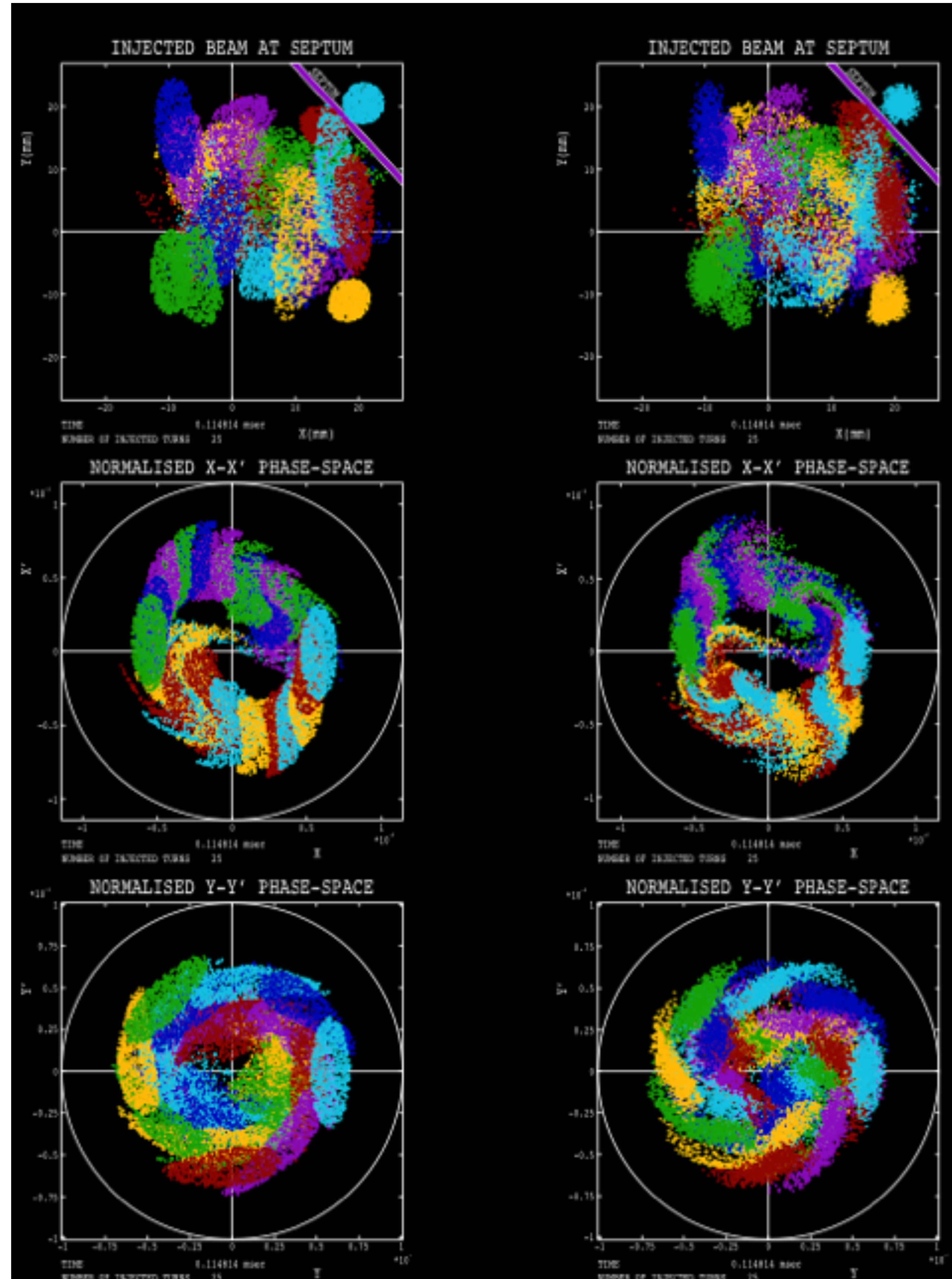
Optimal injection conditions used. Special injection region with trim quads to vary ring optics as injection proceeds



HIDIF–theoretical injection, no space charge



HIDIF with space charge (KV input left, Gaussian right)



Multiturn Injection (Transverse)

- Proton and ion injection via magnetic or electrostatic septum. Liouville's theorem applies and severely restricts the number of turns
  - typically ~10 turns for single plane injection with optimised conditions
  - ~25 turns for two-plane injection
- Inject more turns
  - greater phase space dilution, larger emittance beam in ring
  - beam loss

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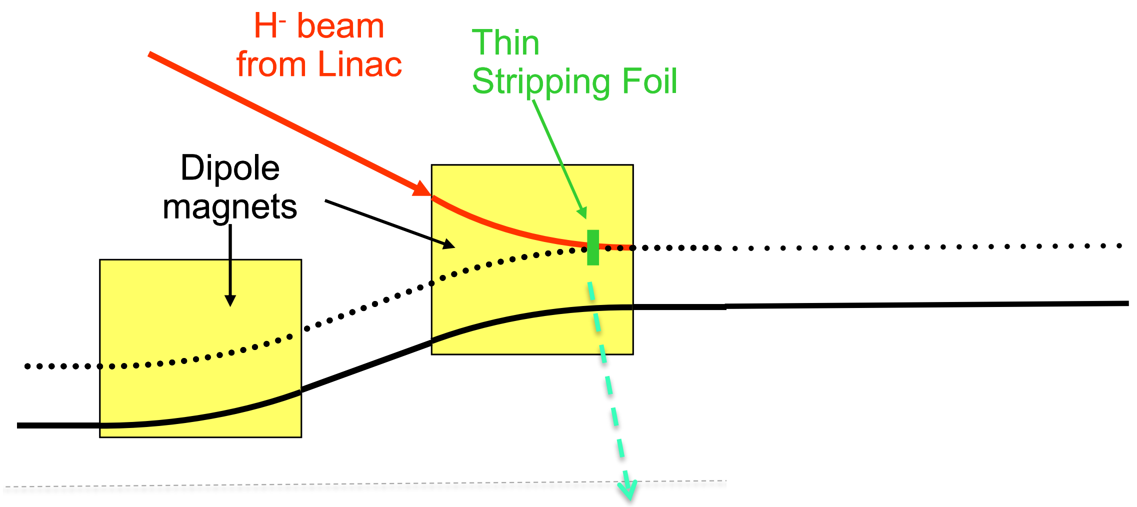
Beating Liouville with H^-

- H^- ions initially accelerated in a linac
- Then injected into a circular accelerator
  - placed in the same phase space volume as an existing bunch of protons already circulating in the ring.
- Possible to have two oppositely charged bunches travelling together in same straight section, since they can be bent in opposite directions by the same magnet.



- In the straight section the beams are passed through a thin foil which strips two electrons from each H^- ion, leaving a single proton beam of higher density in phase space.
- Non-Liouvillean system, allows many more injection turns (several thousand).

Requirements for Next Generation High Power Proton Machines

- Very low levels of (uncontrolled) beam loss - the injection region is a major concern and can dictate many aspects of the design of the machine
  - achieved by removing in advance, at special collectors, beam that is likely to activate the ring
  - requires advanced collimation systems
  - aim is average of 1 W/m of uncontrolled beam loss
- Sophisticated beam accumulation systems.
  - use of H^- beam with charge-exchange injection
  - gaps chopped in linac bunch train to minimise longitudinal beam loss
  - achromatic arc to remove linac beam halo prior to injection
  - phase space "painting techniques" to create required transverse distribution and good longitudinal bunching factor to lower space-charge

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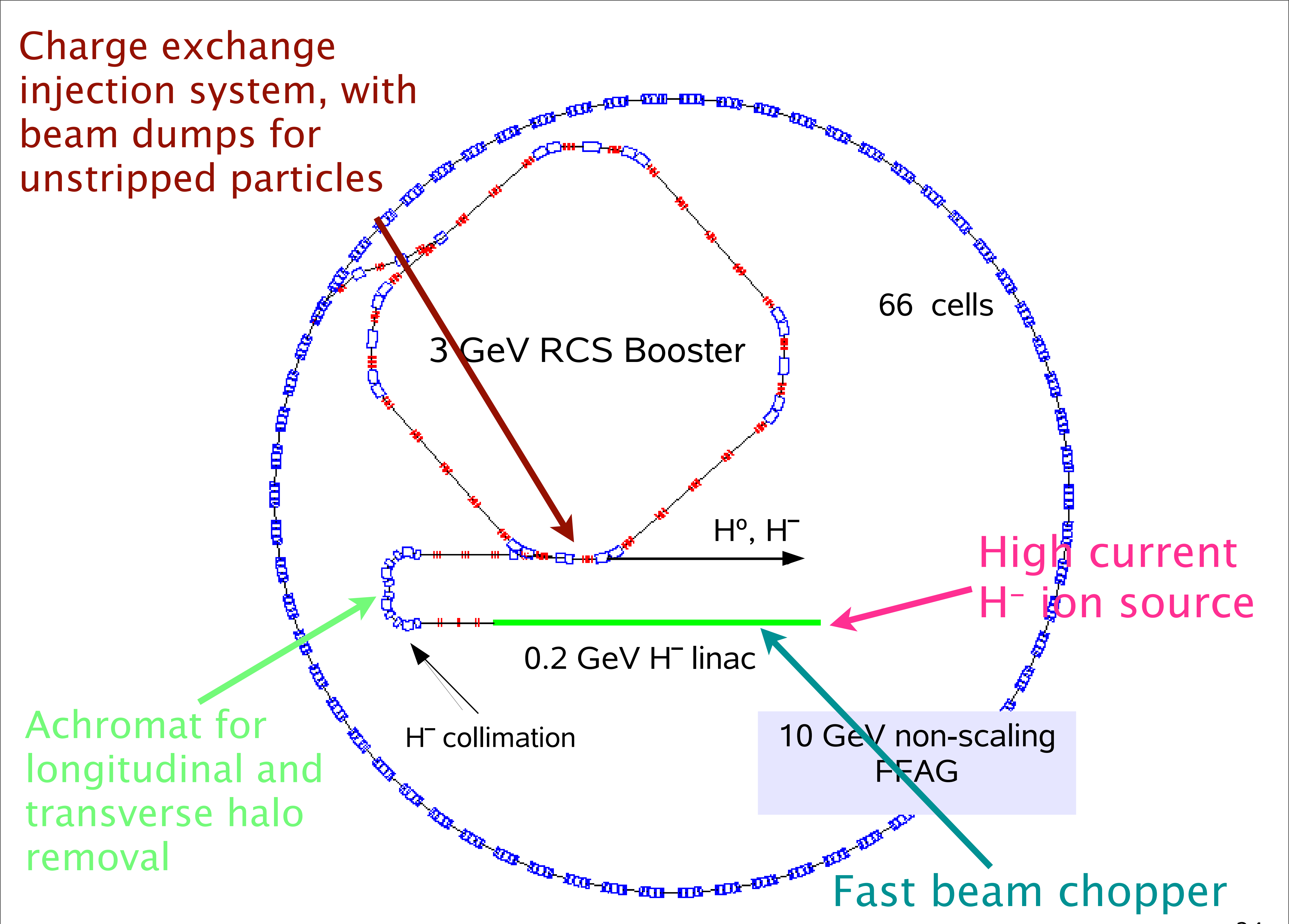
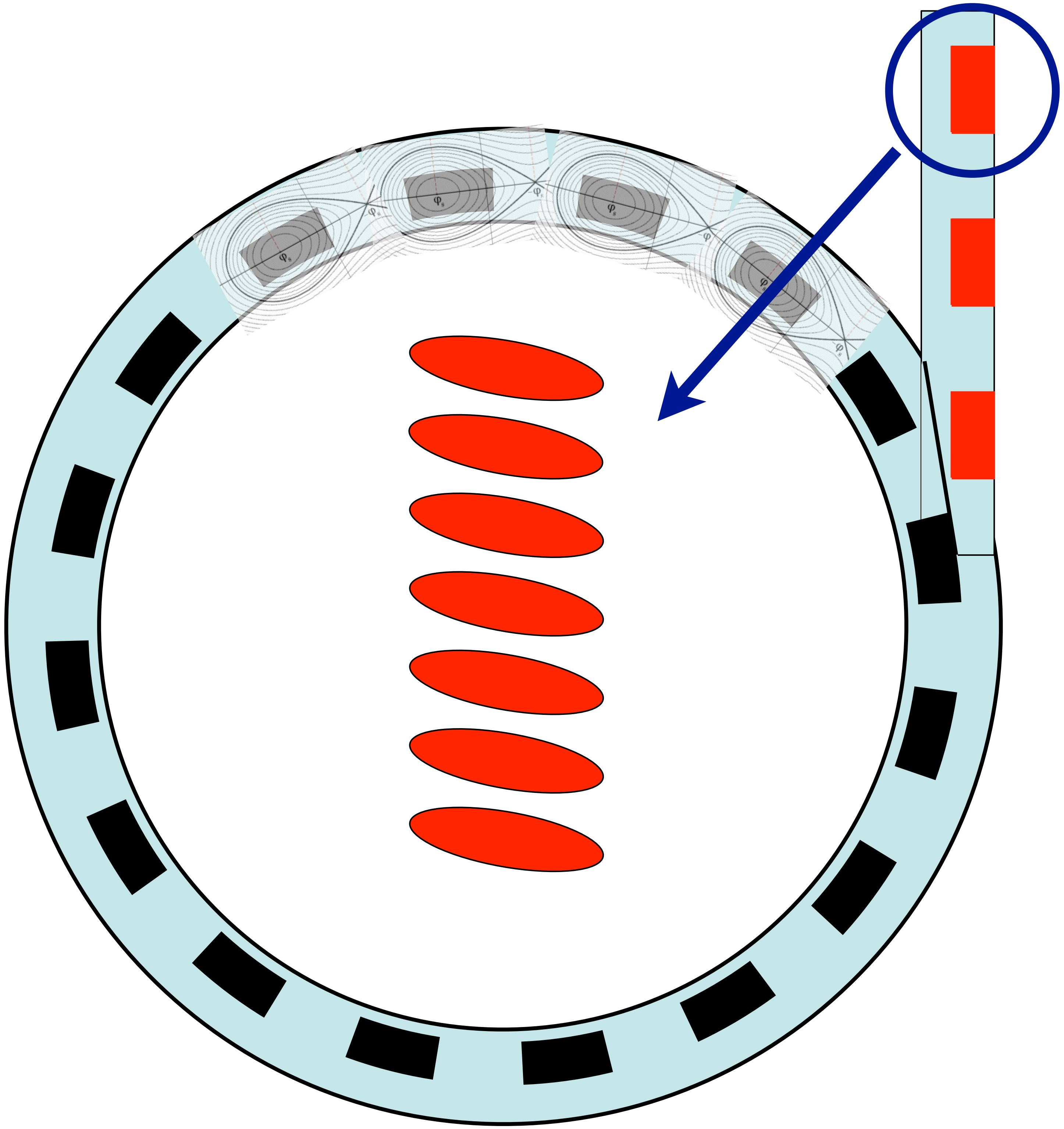
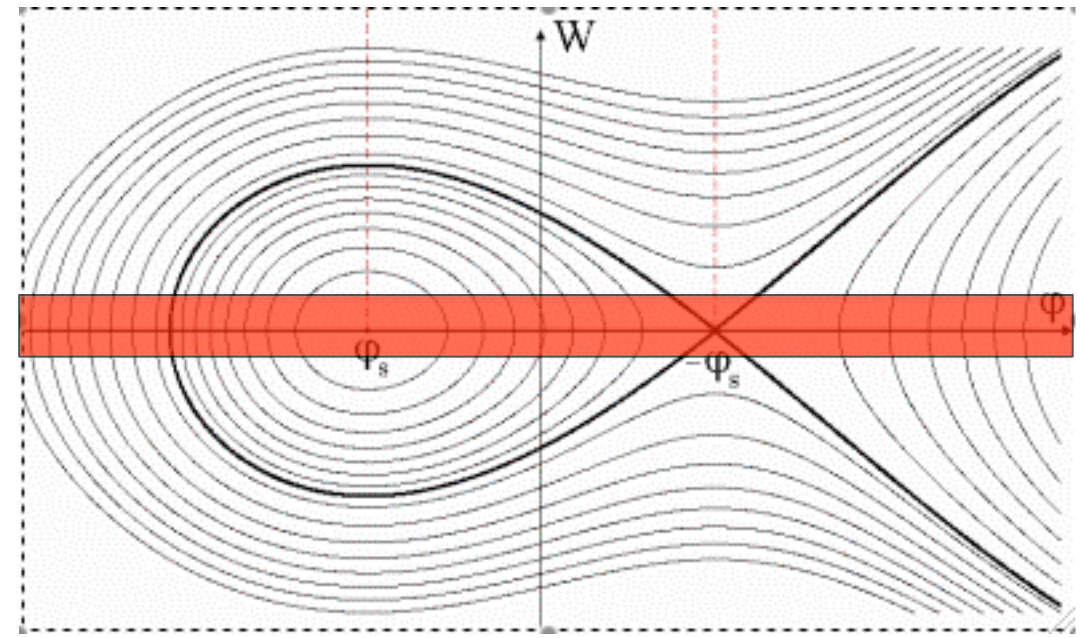

Charge exchange injection system, with beam dumps for unstripped particles
66 cells
3 GeV RCS Booster
Hº, H⁻
High current H⁻ ion source
0.2 GeV H⁻ linac
Achromat for longitudinal and transverse halo removal
H⁻ collimation
10 GeV non-scaling FFAG
Fast beam chopper

Need for Chopping





- If incoming beam is continuous in phase, all particles outside rf separatrix (bucket) are likely to be lost.
- Ring will be irradiated and hand-on maintenance not possible.

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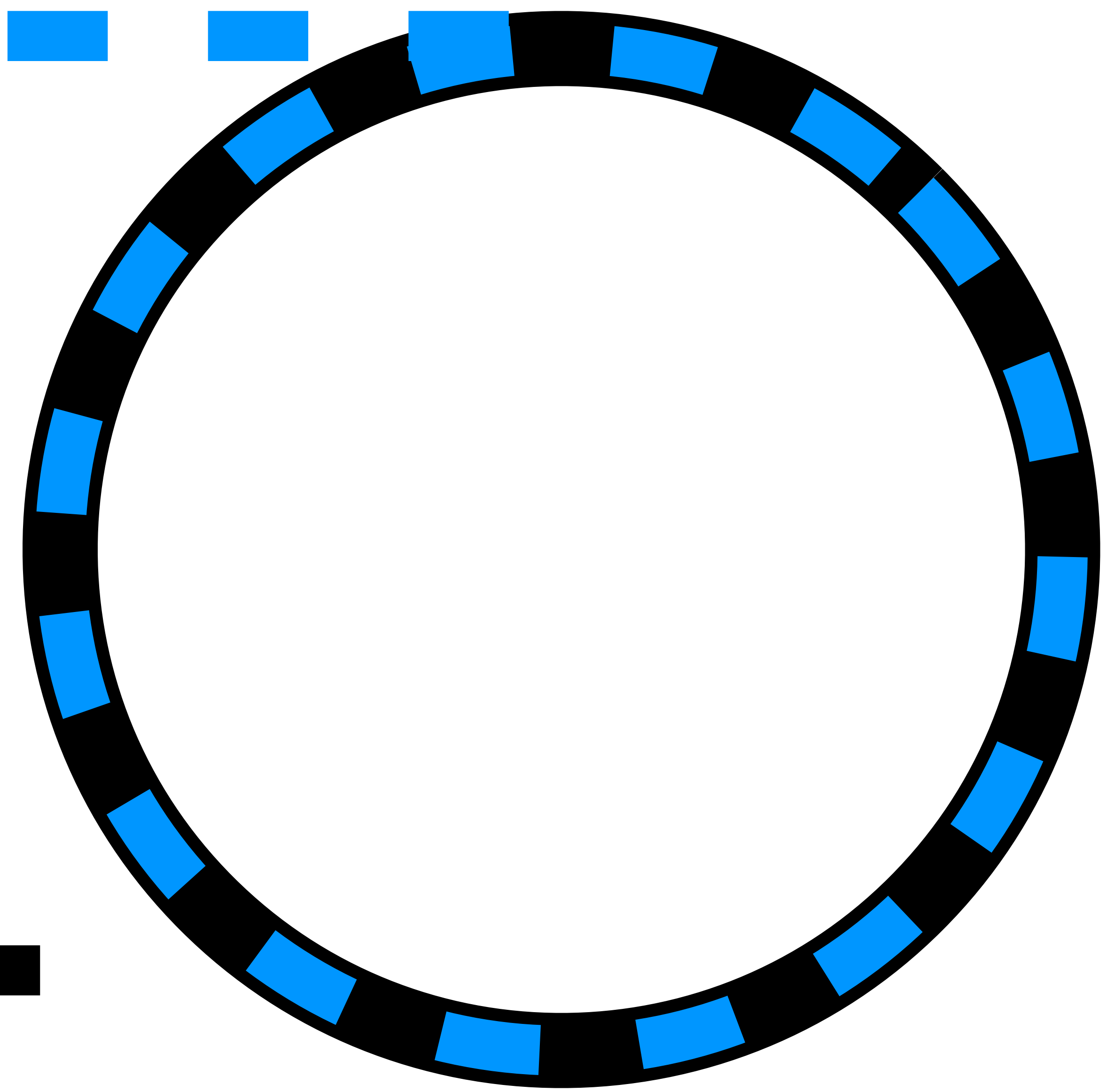
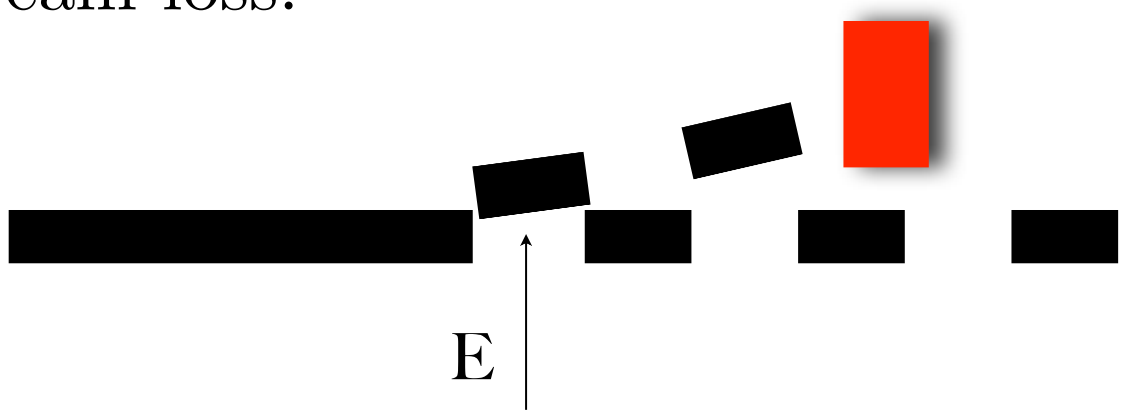
Fast Beam Chopper

Create gaps in the linac beam so that bunches fit together in the ring, leaving gaps for eventual ring extraction. All particles fall in stable regions of longitudinal phase space, so minimising beam loss.





Linac frequency (say) 330 MHz $\Longrightarrow$ train of micro-bunches separated by 3 ns.

Bunches can be diverted to dedicated beam dumps by electrostatic deflector, but rise time has to be $\lesssim 2.5$ ns for clean chopping.

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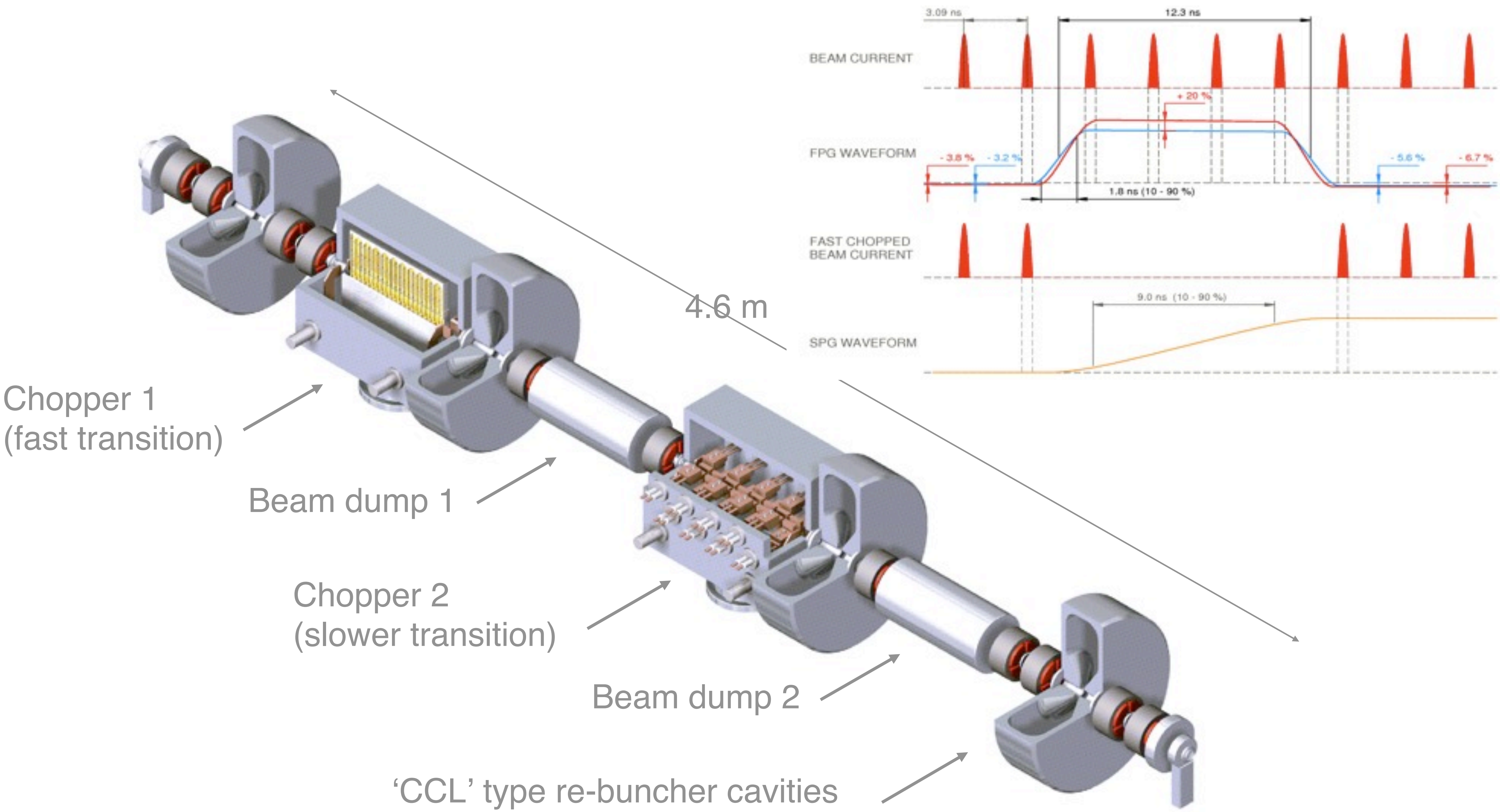
RAL 3.0 MeV Chopper, 324 MHz



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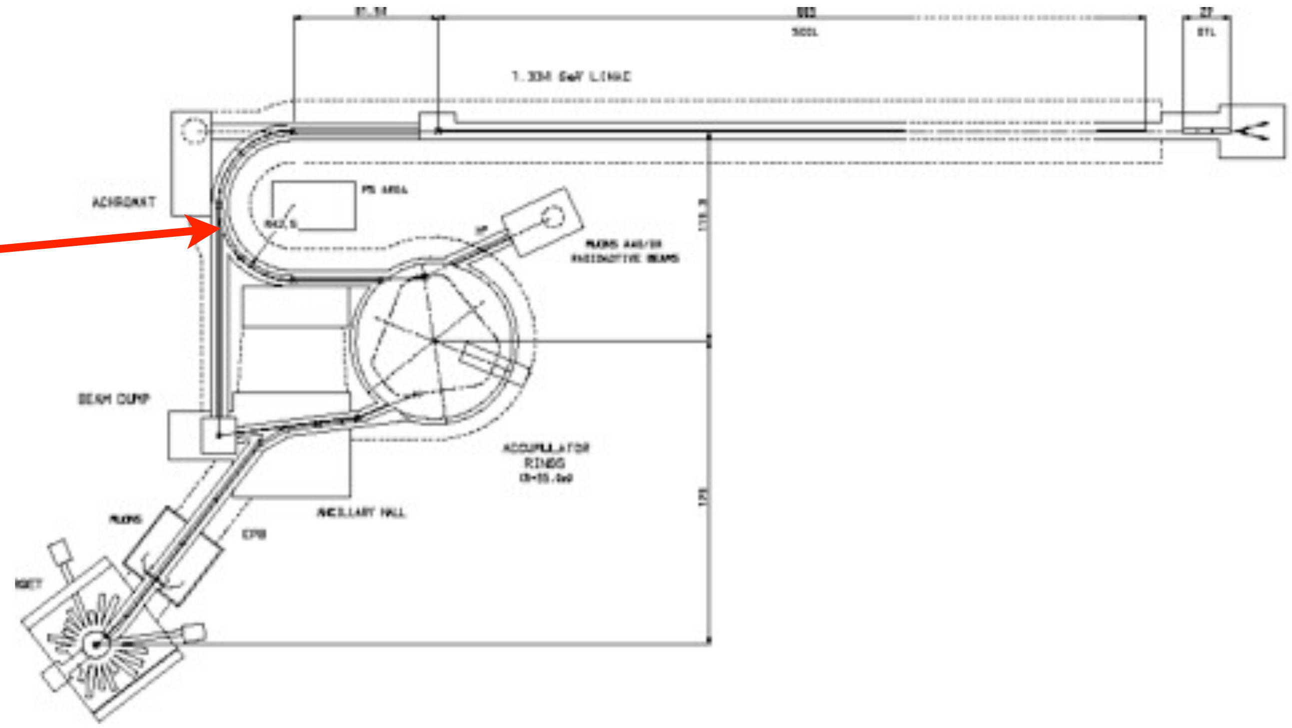
Achromat

Achromatic arc between linac and ring



- Halo on the linac beam will give injection losses that are difficult to localise
- Purpose of the achromat is to strip this halo (transversely and longitudinally) and prepare the beam for ring injection
- Achromat adjusts momentum spread and focuses the beam to the correct spot size on the injection foil

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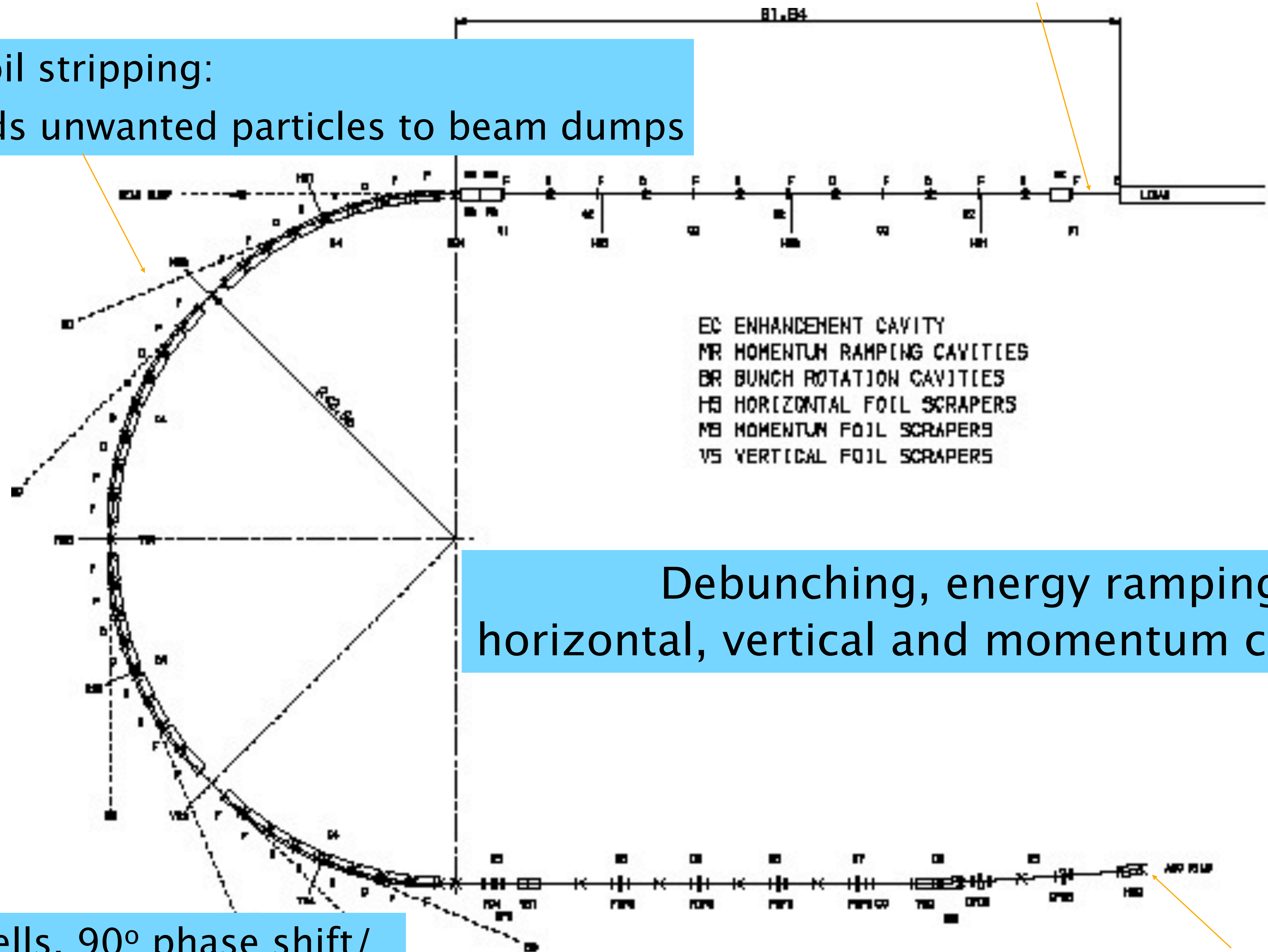
Linac focusing structure continued for smooth

H^- foil stripping:

bends unwanted particles to beam dumps

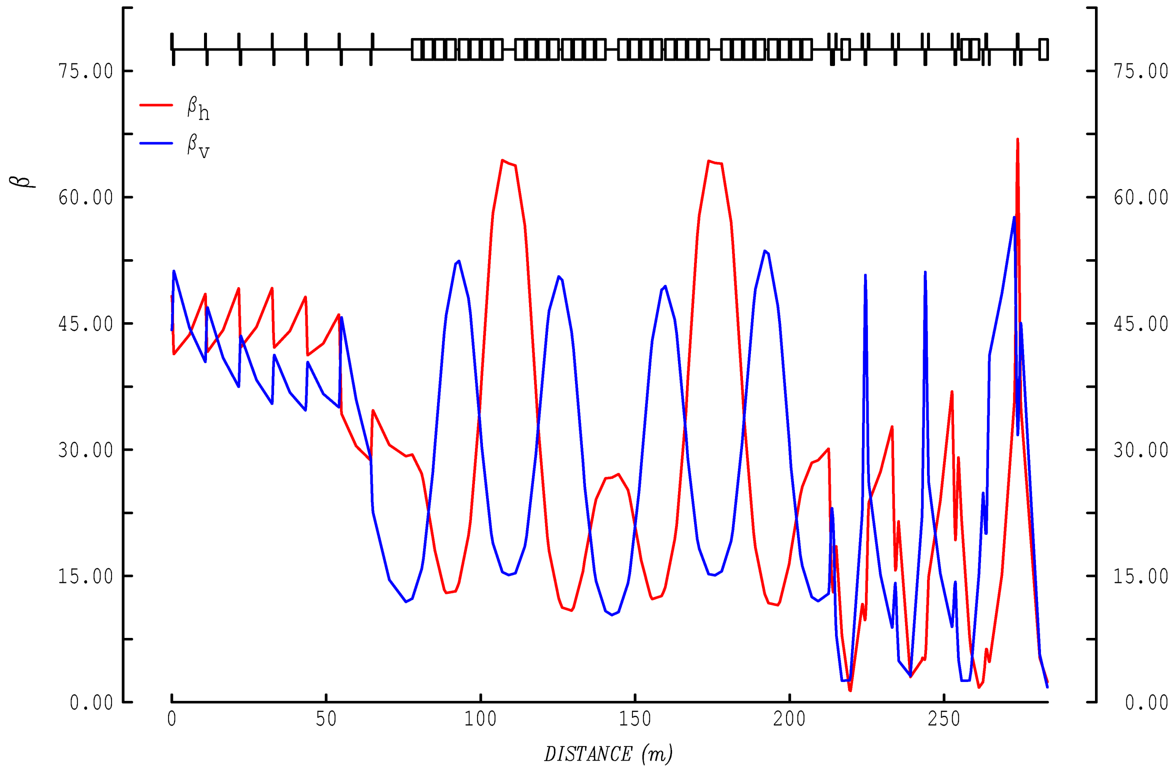


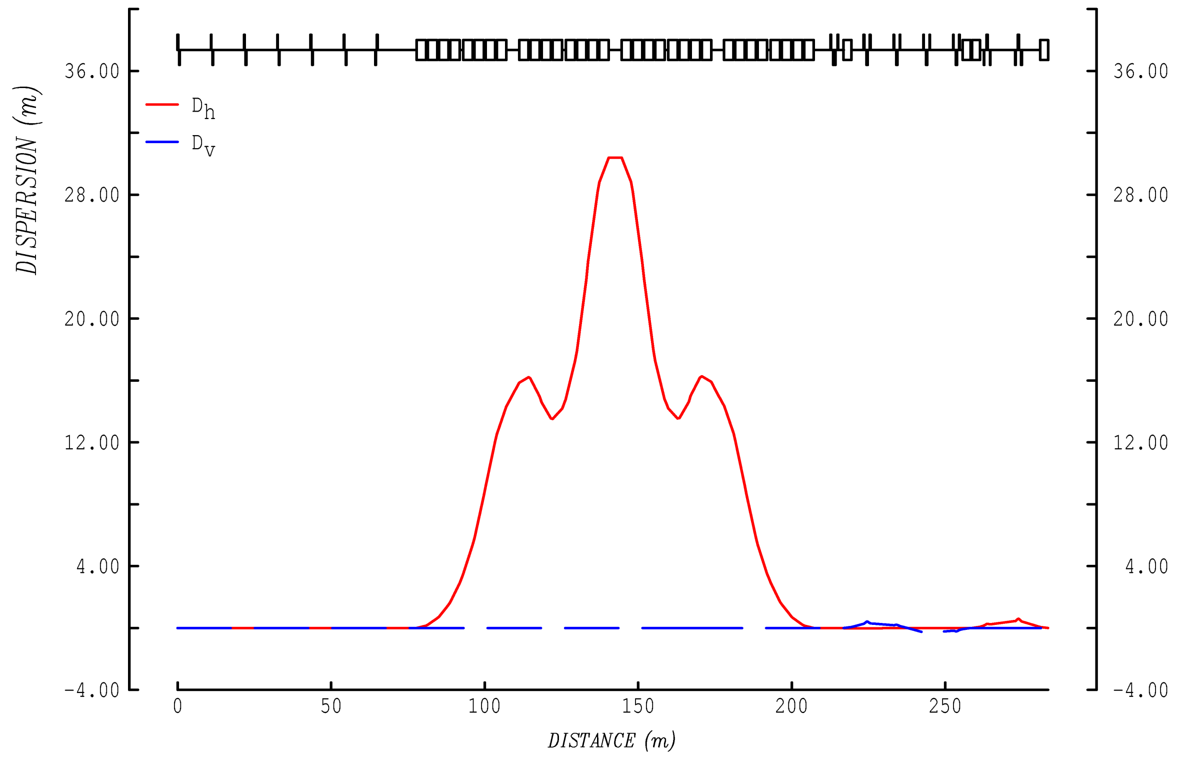
Debunching, energy ramping, horizontal, vertical and momentum collimation

4 cells, 90º phase shift/ cell

Match parameters to required spot size for injection

Typical Achromat Lattice Functions





Longitudinal halo removed through the use of a high normalised dispersion:

$$x = x_\beta + D_x \frac{\Delta p}{p} = \sqrt{\beta}\left(\sqrt{\epsilon} + \frac{D_x}{\sqrt{\beta}}\frac{\Delta p}{p}\right).$$

$\frac{D_x}{\sqrt{\beta}}$ is the *normalised dispersion*

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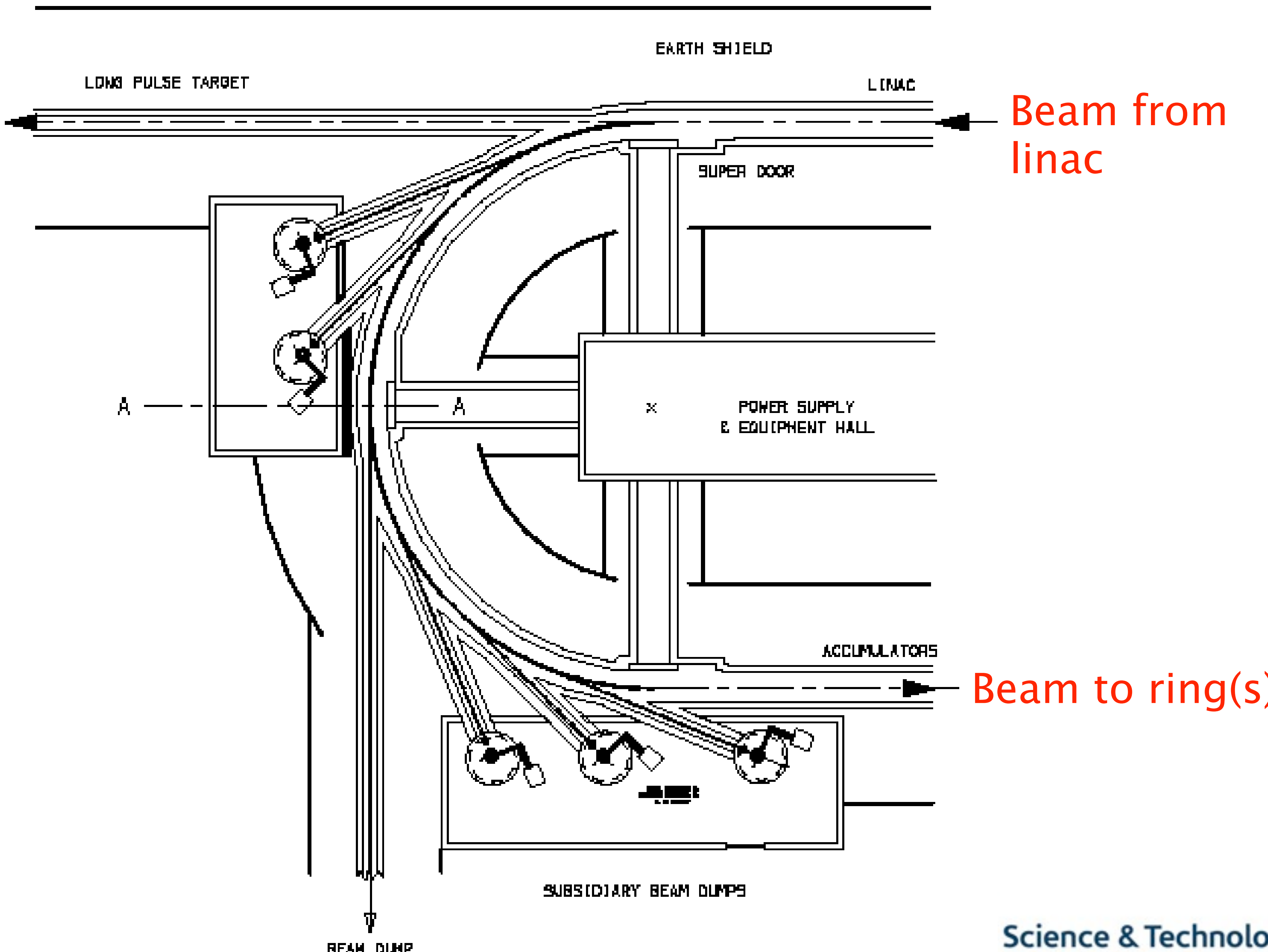
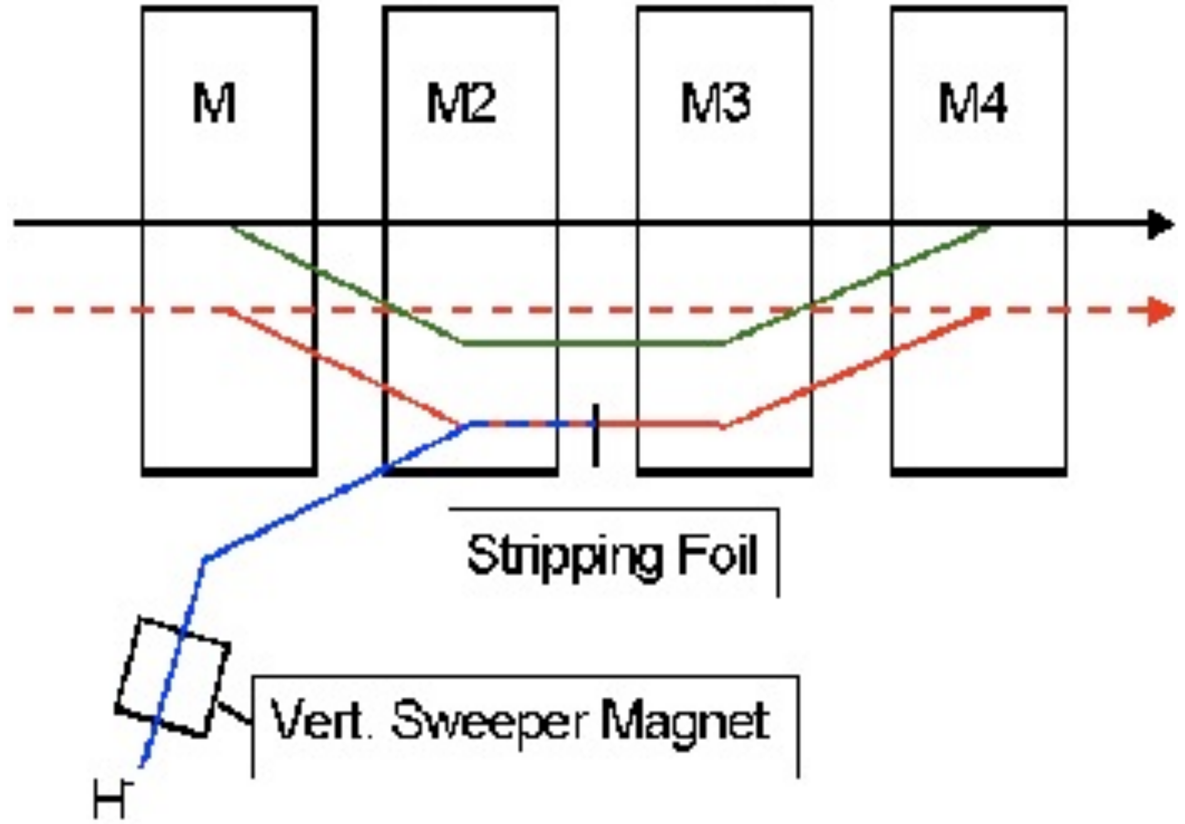
Achromat Design Plan 2002



Accumulation of Particles in a Ring

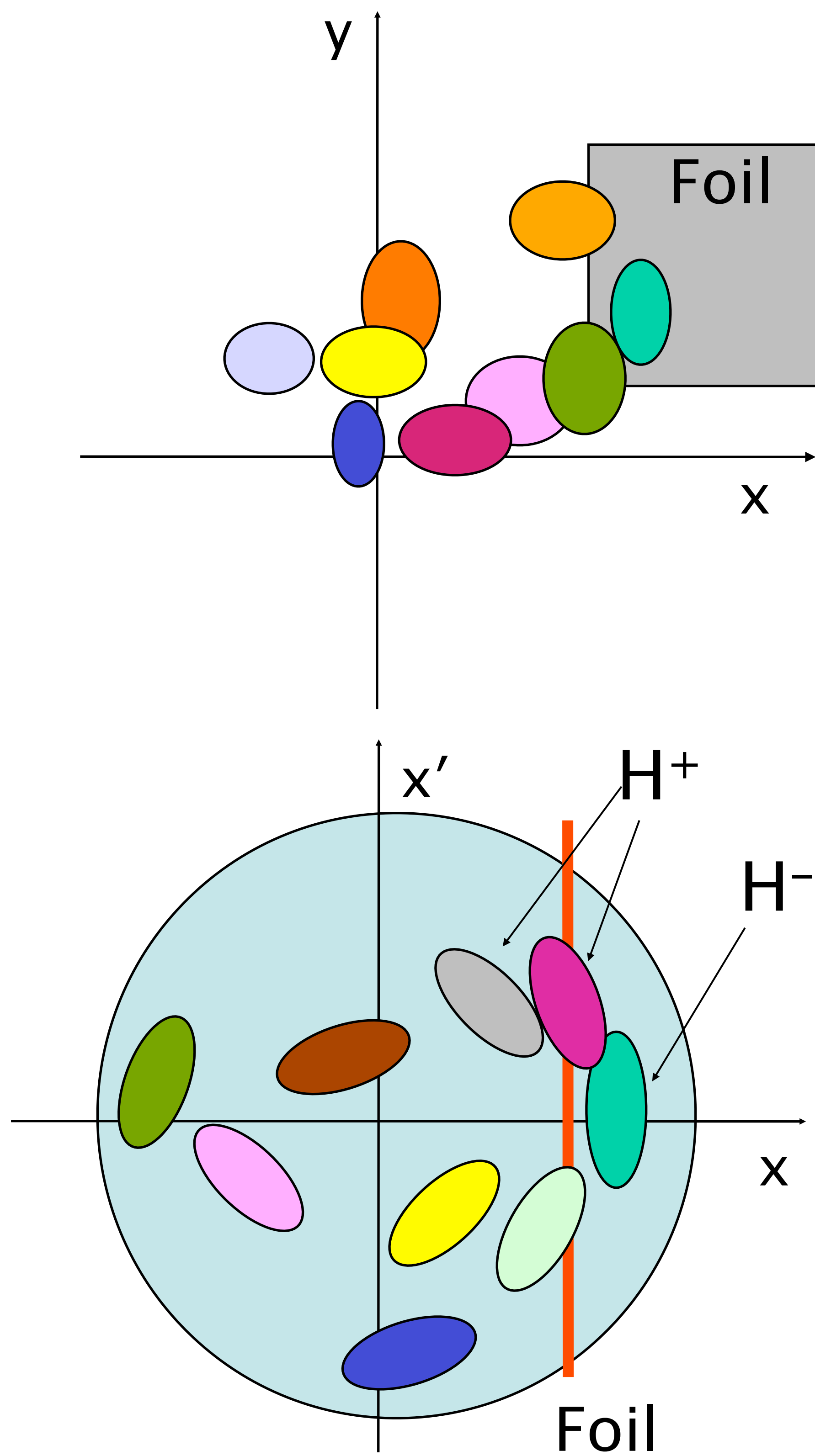
Object: to increase beam intensity.

For spallation sources and neutrino factories need to inject ~10^{14} protons per pulse



Closed orbit bump magnets move circulating particles out to combine with incoming beam. Enhanced beam is then moved back onto the ring central orbit.

Charge Exchange Injection (H^-)



- H^- is converted to H^o, then H^+ through removal of two electrons with a stripping foil
- H^+ can be overlaid on H^- in phase space (non-Liouvillean)
- Any number of turns can be injected
- Recirculating protons can pass through foil
- Flexibility: allows phase space painting for improved beam distribution and reduced space charge effects

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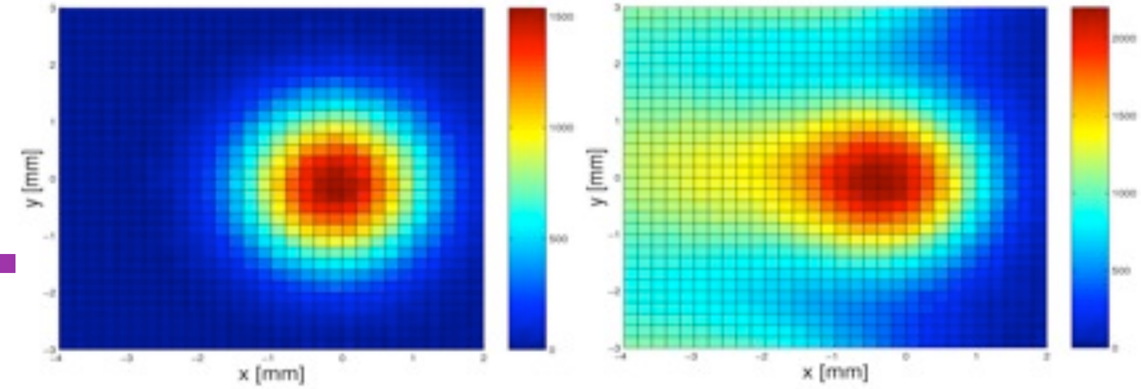
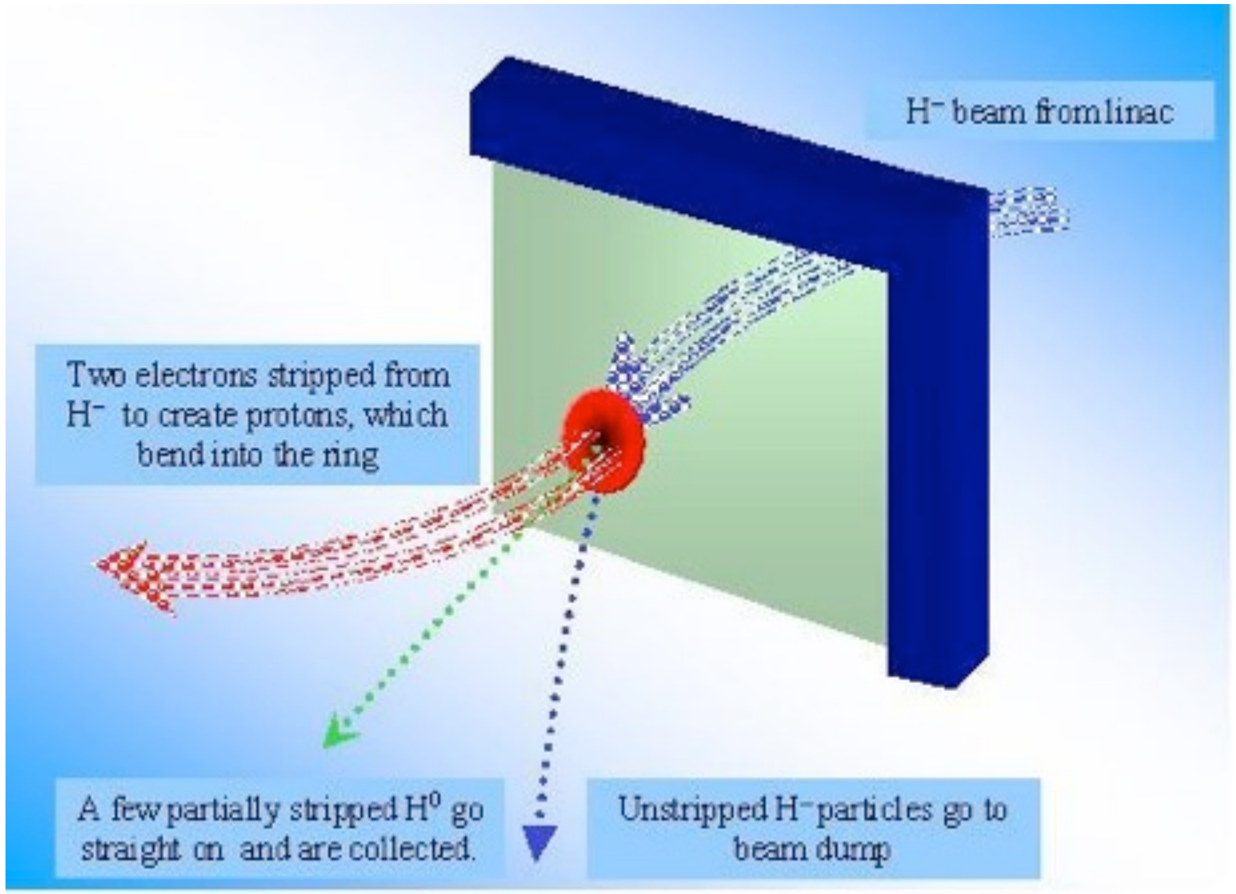
Injection into a Ring



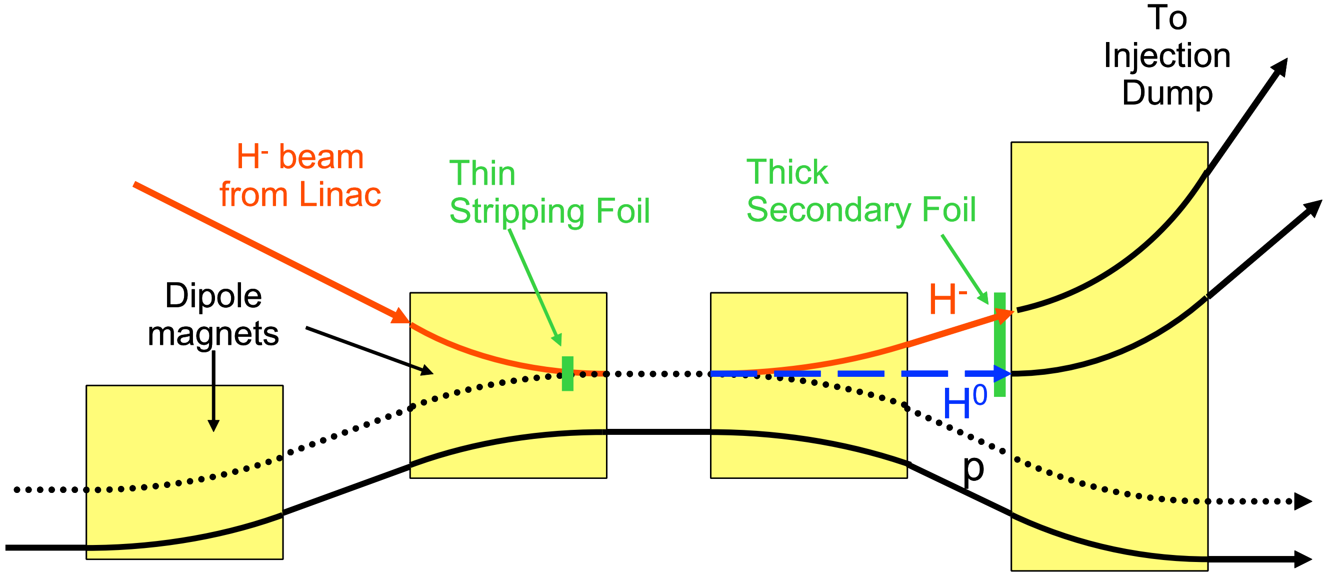
- Proton beam created by stripping two electrons from H^- ions
- Beam in ring has to be painted from incoming linac beam
- Aim is to create as uniform a distribution as possible and try not to burn out the stripping foil

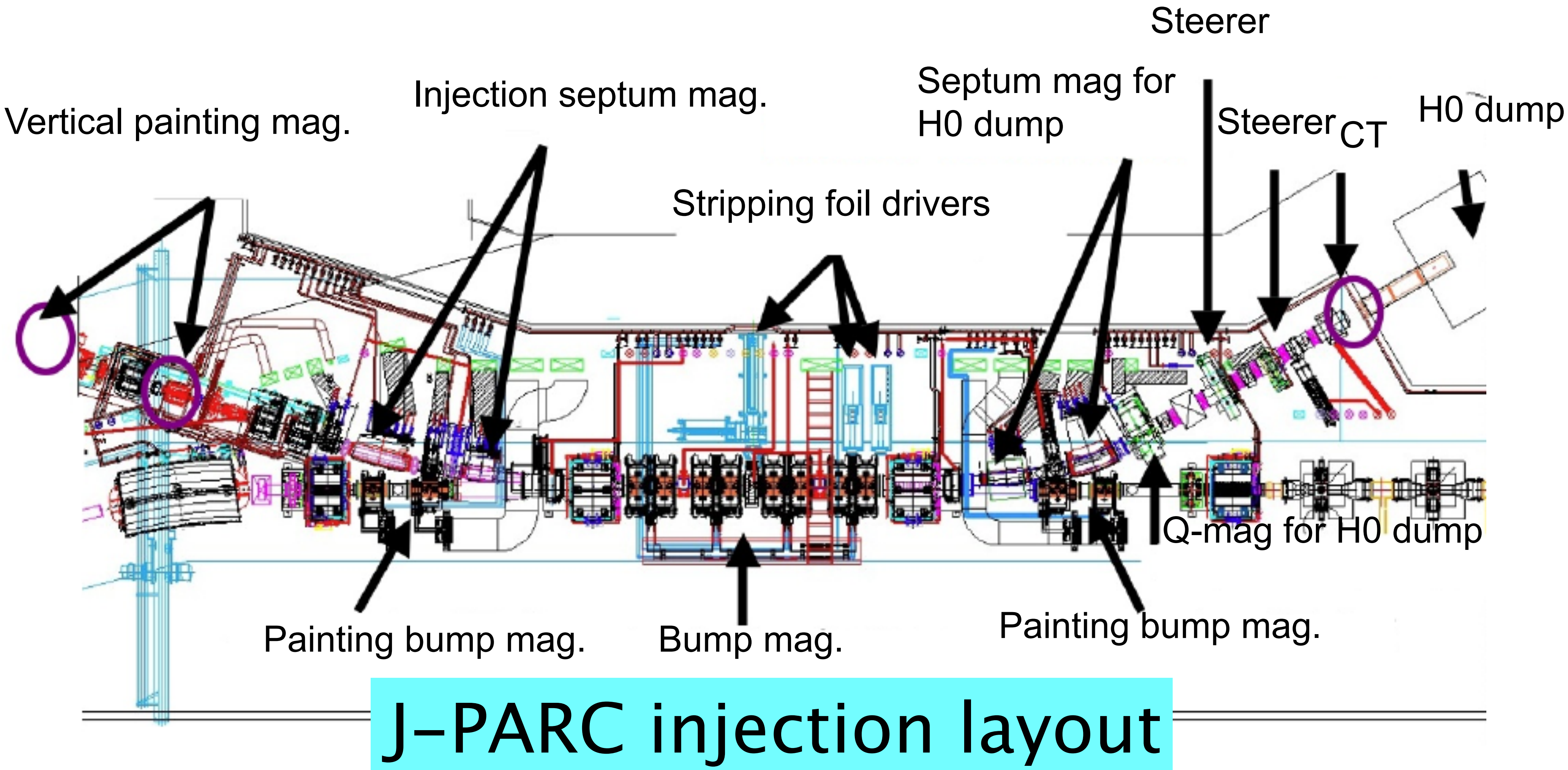


- Handling unstripped H^- and H^0
  - beam dumps
  - extra foils
  - choice of beam energy
- Foil issues
  - scattering, heating, stress, buckling
  - lifetime
  - radiation
  - stripped electrons
  - emittance growth

Injection Geometry

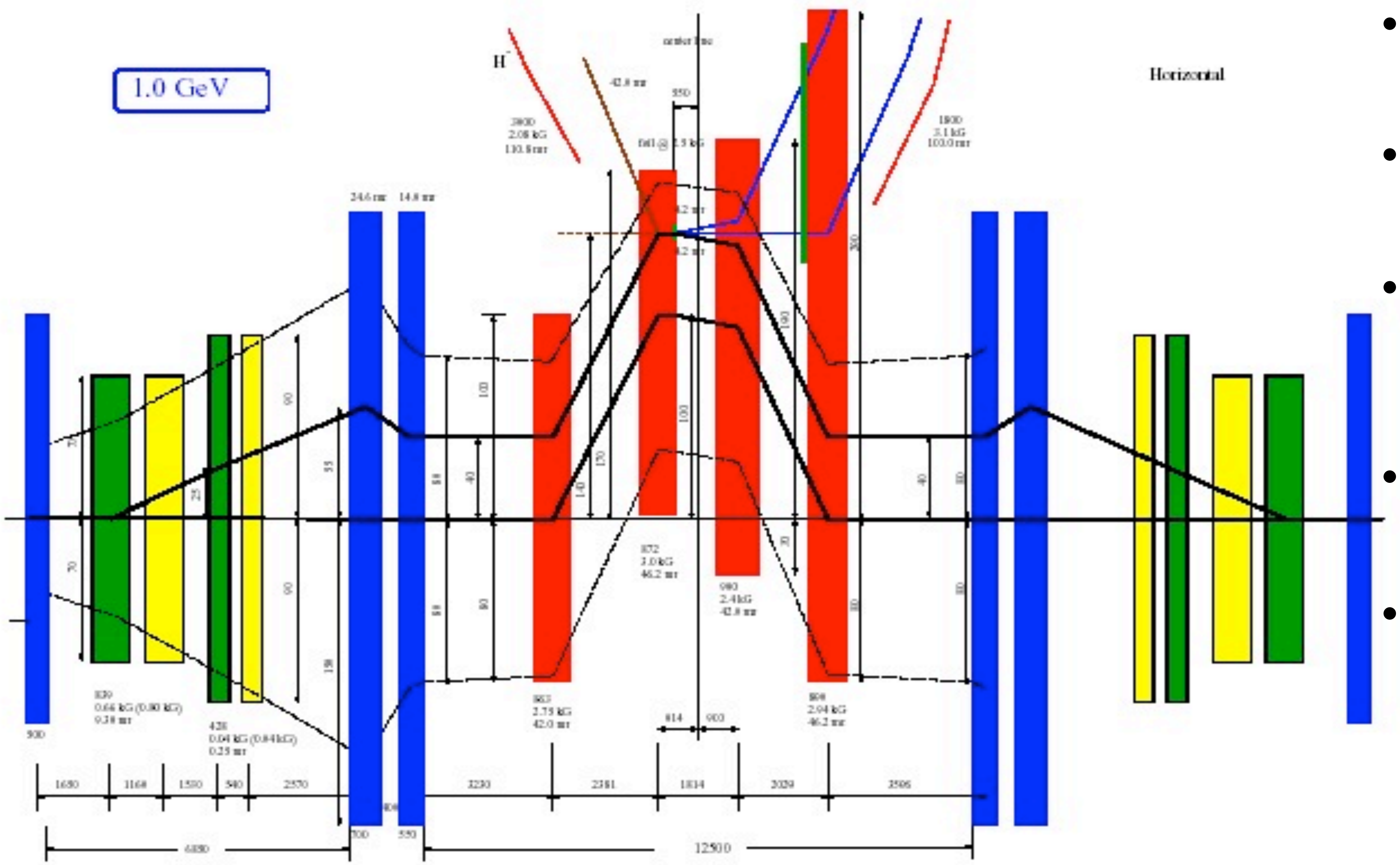
- Injection region is one of the most complicated parts of a proton driver and one of the hardest to simulate.
- The injection straight is an area of high uncontrolled beam loss, mainly from foil scattering. Requirement is to keep this at 1 part in 10^4





SNS Injection

Uses horizontal and vertical orbit bumps to paint the beam



- Independent H, V, L control
- Circular & square profile both attainable
- Energy corrector & spreader in beam transport line to ring
- Tolerable to momentum errors
- Small residual Δβ/β & dispersion at injection position

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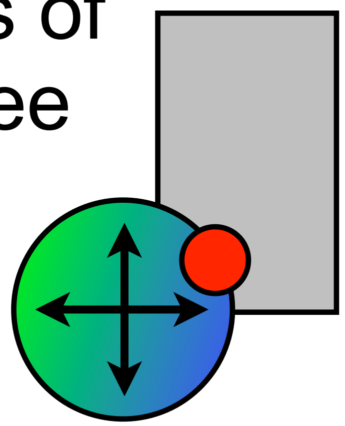
Transverse Injection Painting

- Vary position of circulation beam at the foil by a series of programmed orbit bumps (H and V) in a dispersion-free region.
  - adopted at SNS and J-PARC



- Vary direction of incoming linac beam in one phase plane, programmed orbit bumps in the other
  - preferred at Fermilab
- Inject in a dispersive region and paint using dispersion by varying incoming beam energy
  - used at ISIS and in all RAL proton driver designs

$$x = D\frac{\Delta p}{p}$$

- Painting in two independent phase planes can be correlated or anti-correlated.

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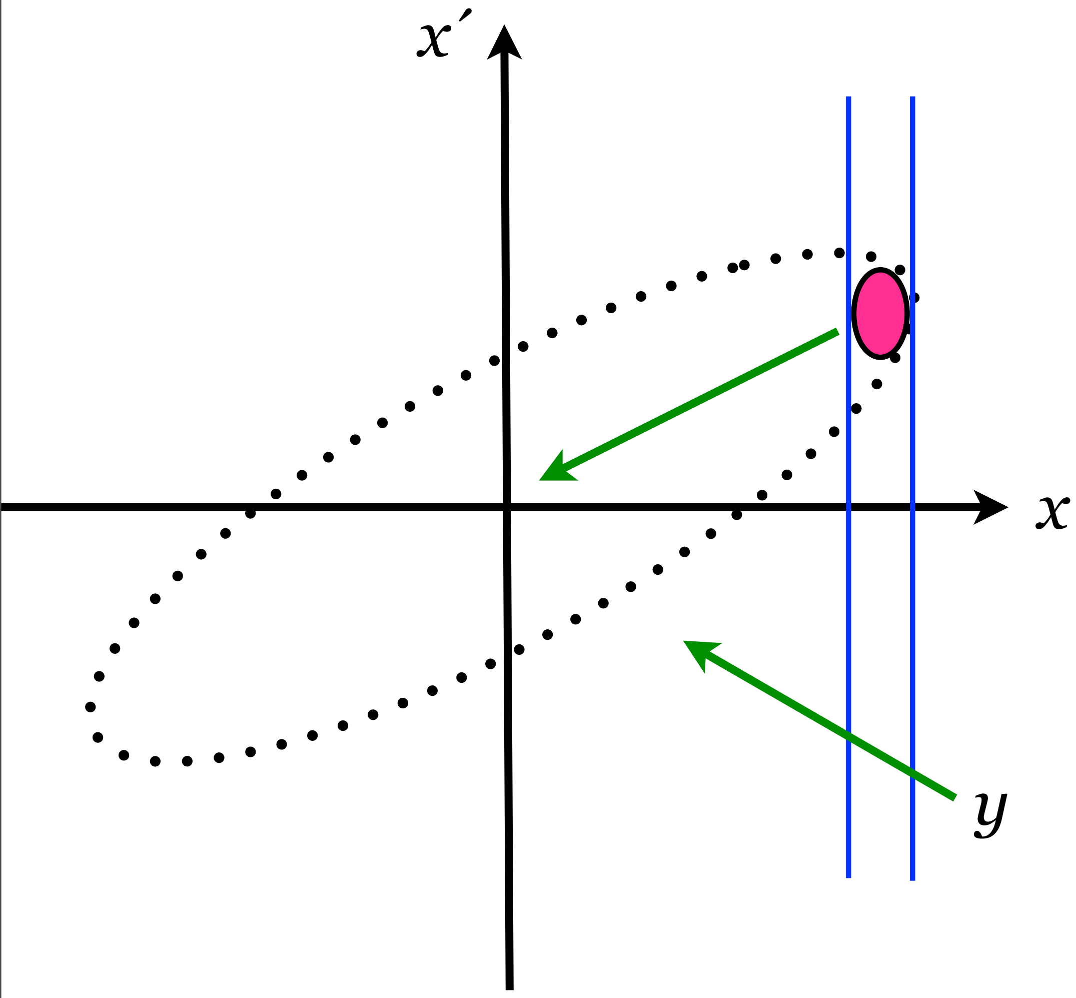
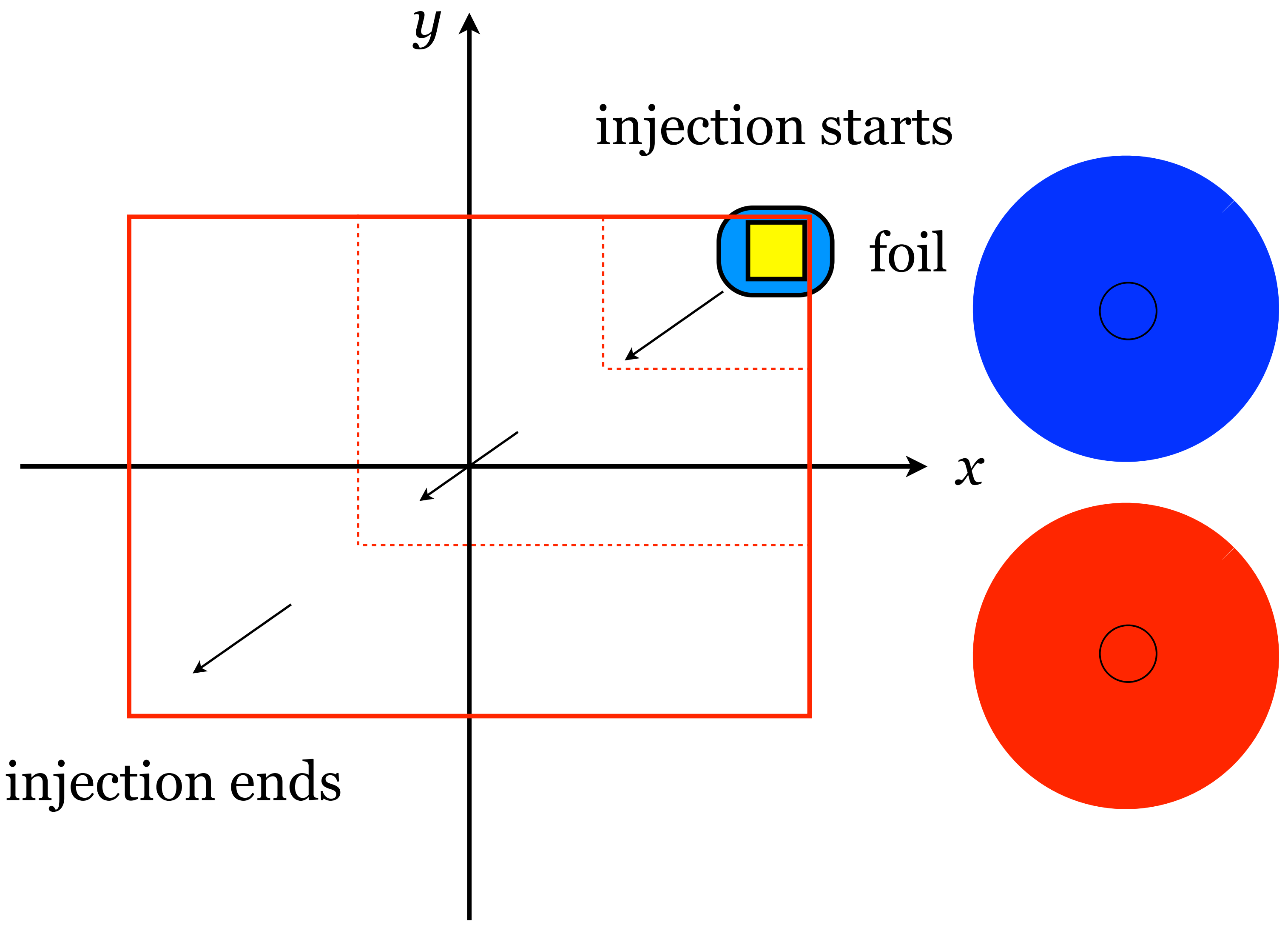
Correlated painting

Both horizontal and vertical orbit bumps produce oscillations progressing from small to large amplitude (or large to small)





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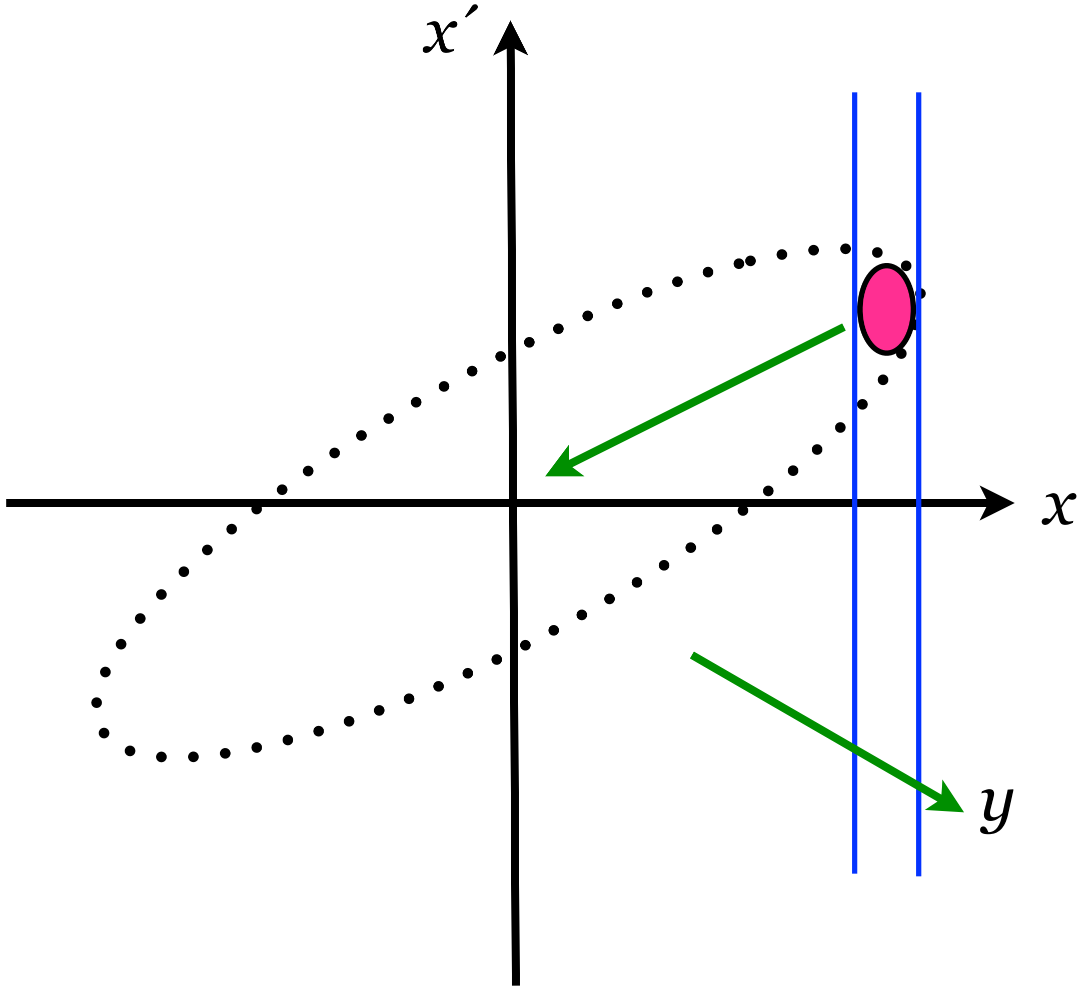
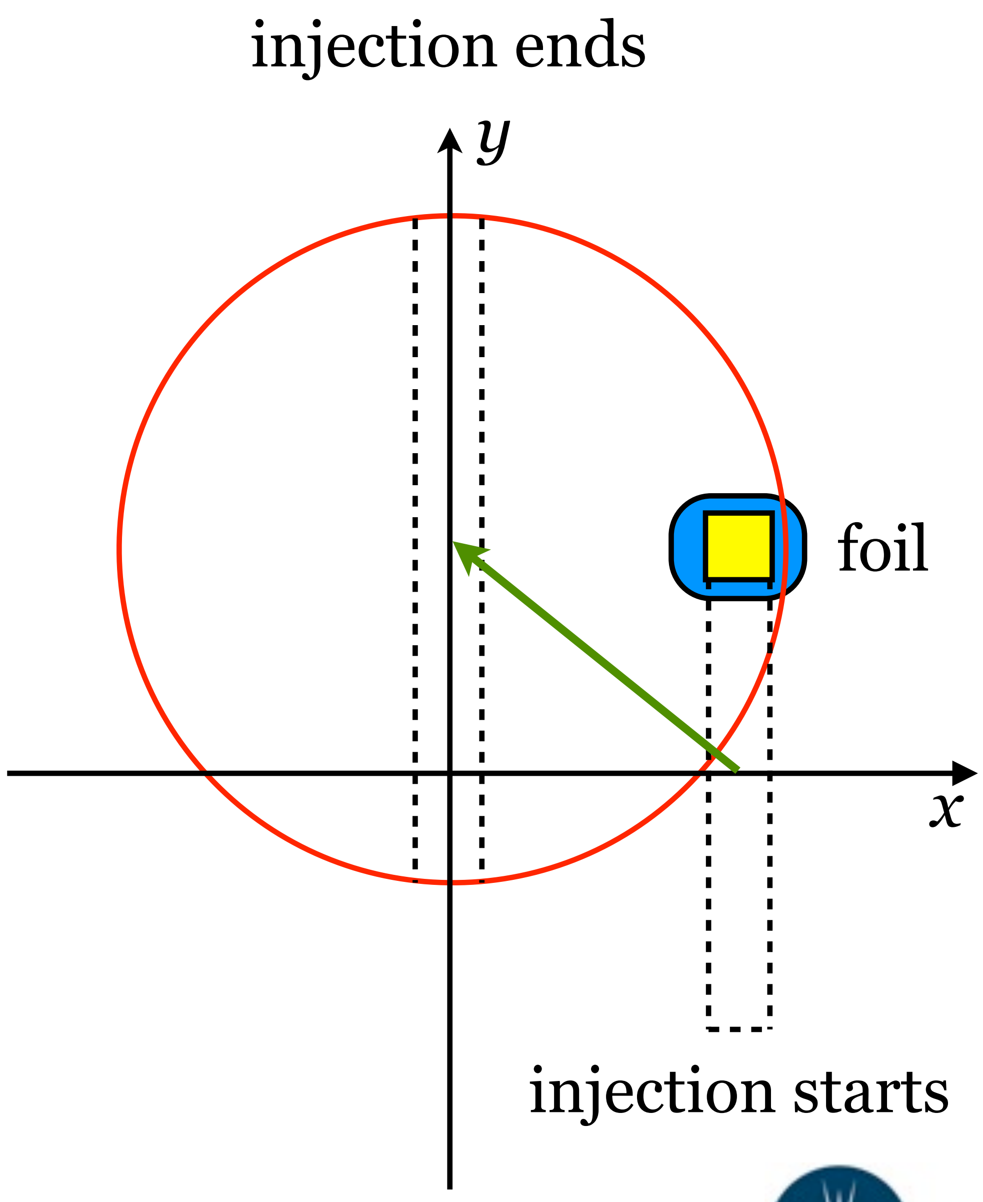
Anti-correlated painting

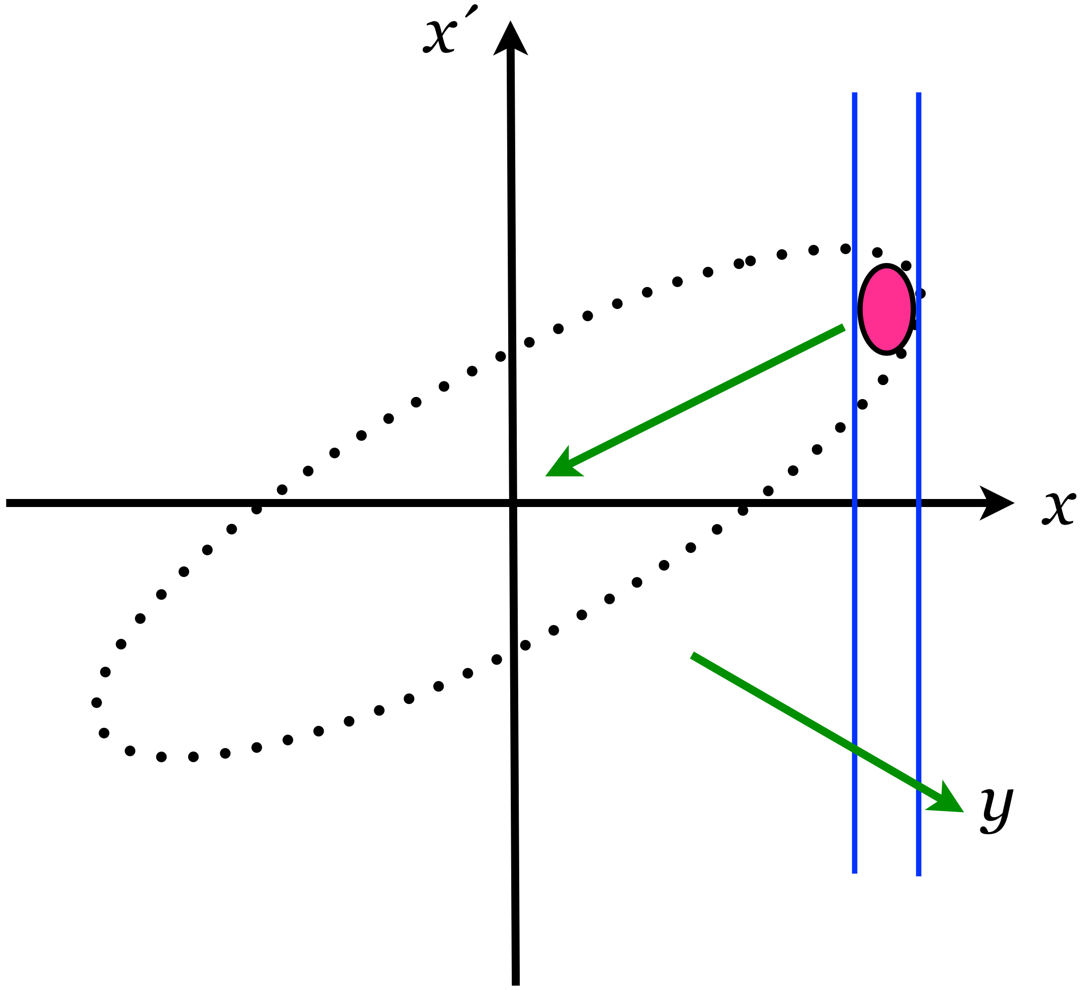
Oscillations vary from small to large amplitude in one plane, large to small in the other.

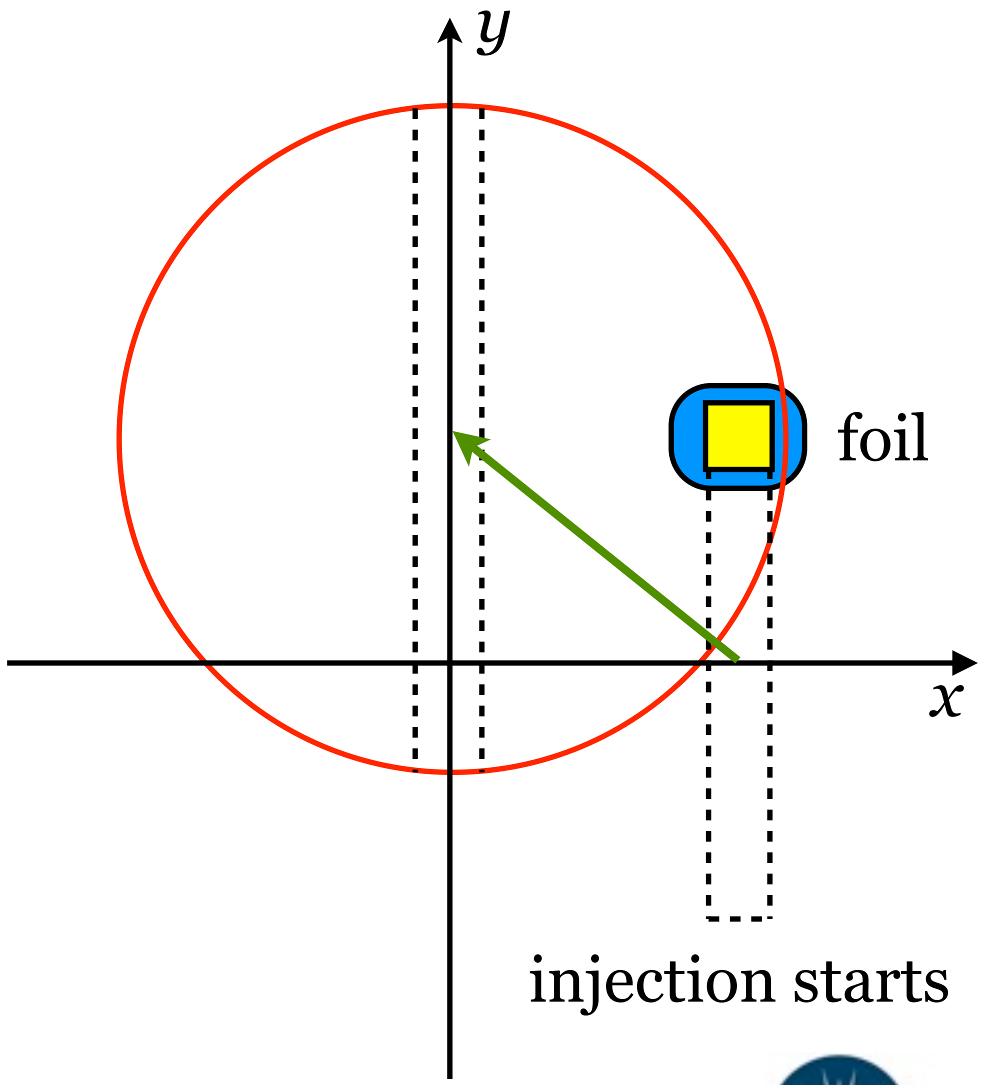


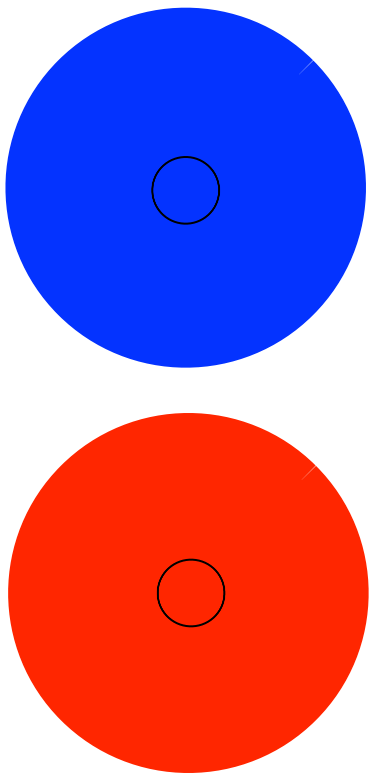


Anti-correlated painting

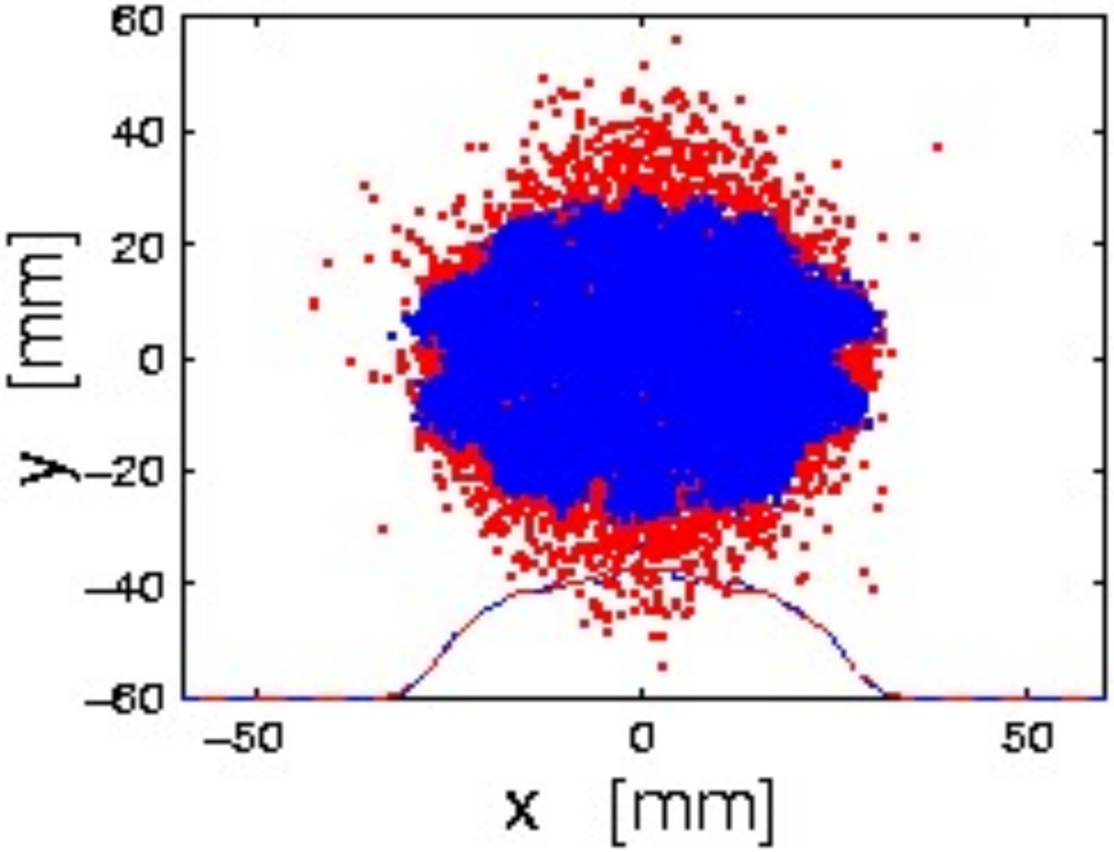
Oscillations vary from small to large amplitude in one plane, large to small in the other.

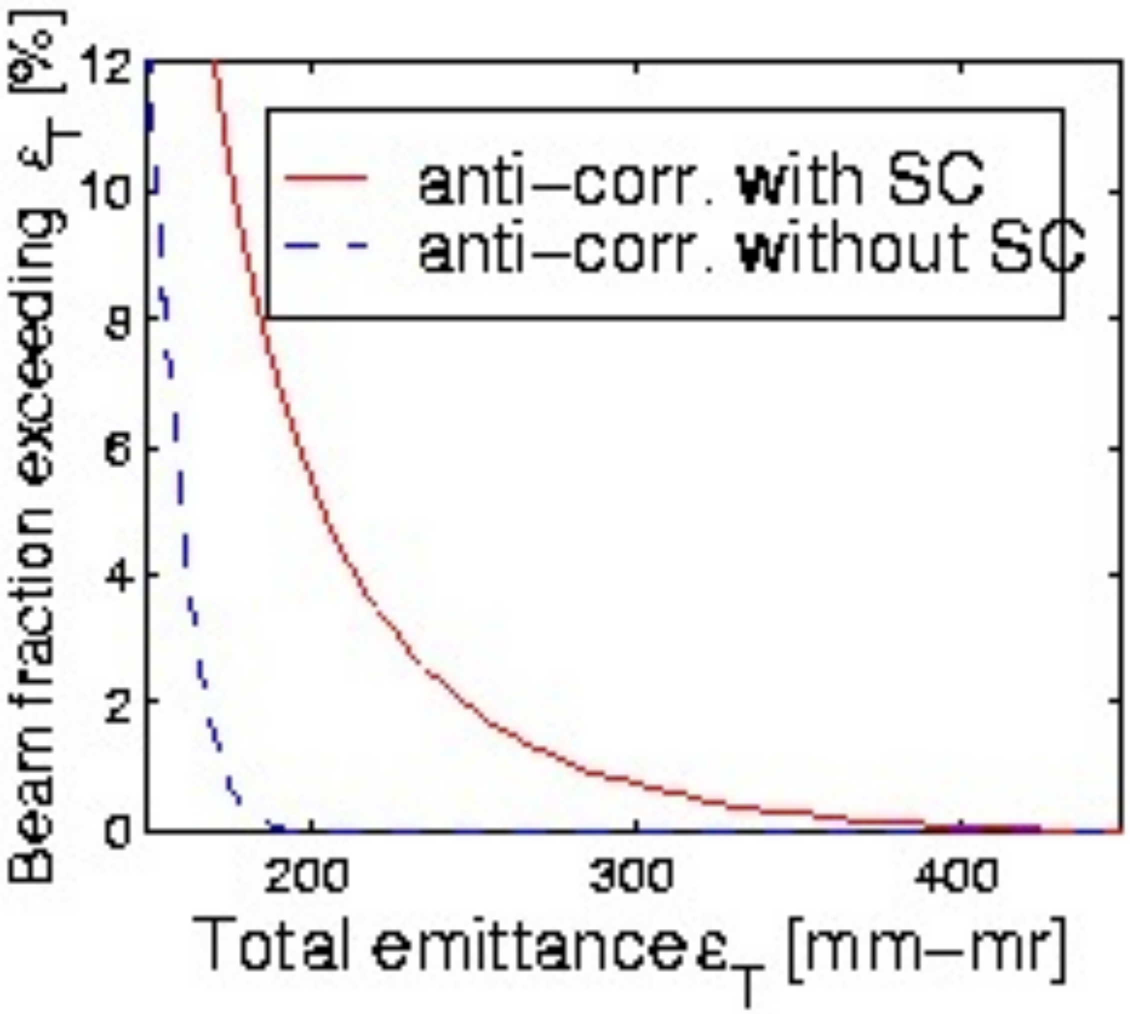






Space charge & halo formation





Disadvantage of not painting over the halo

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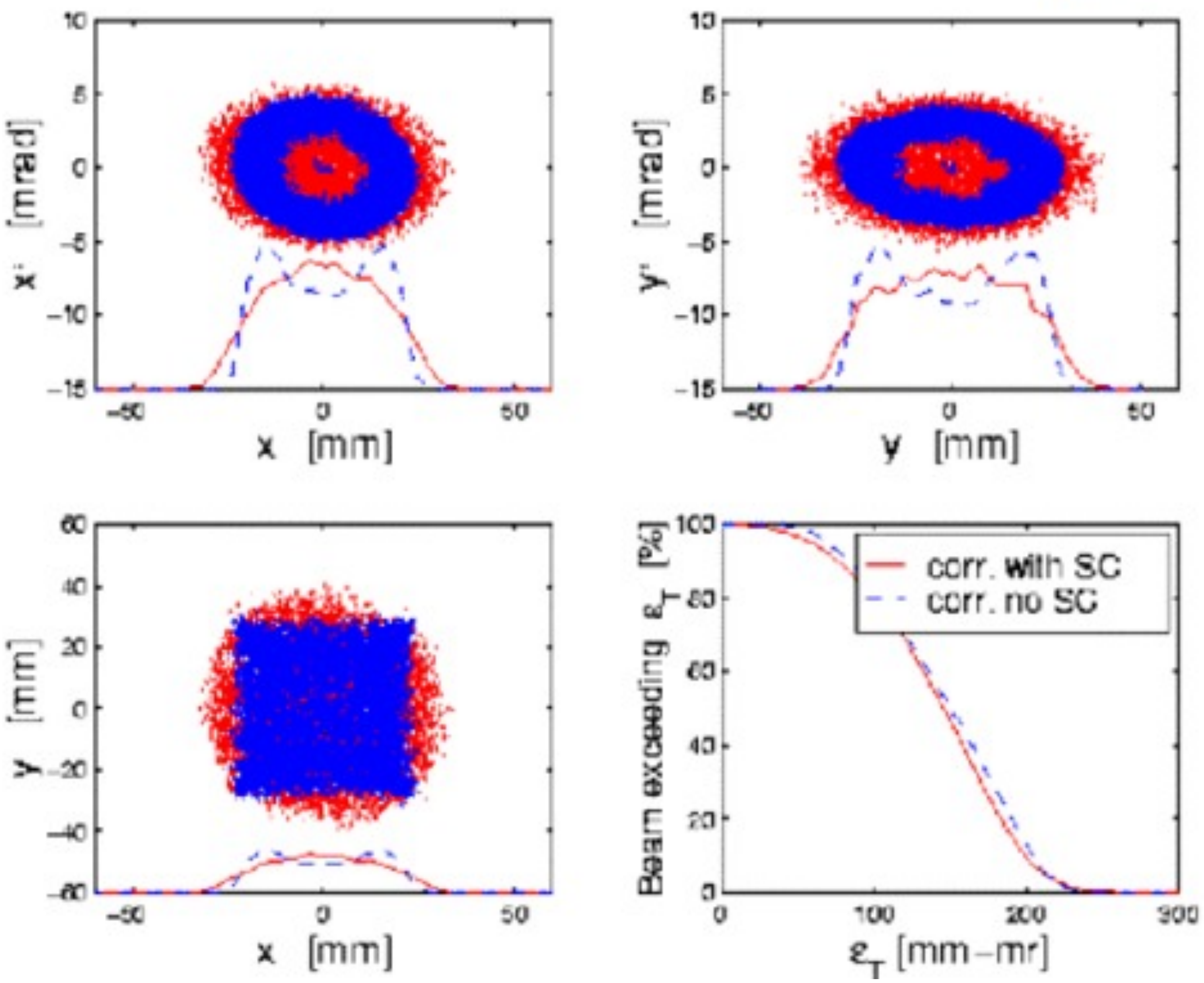
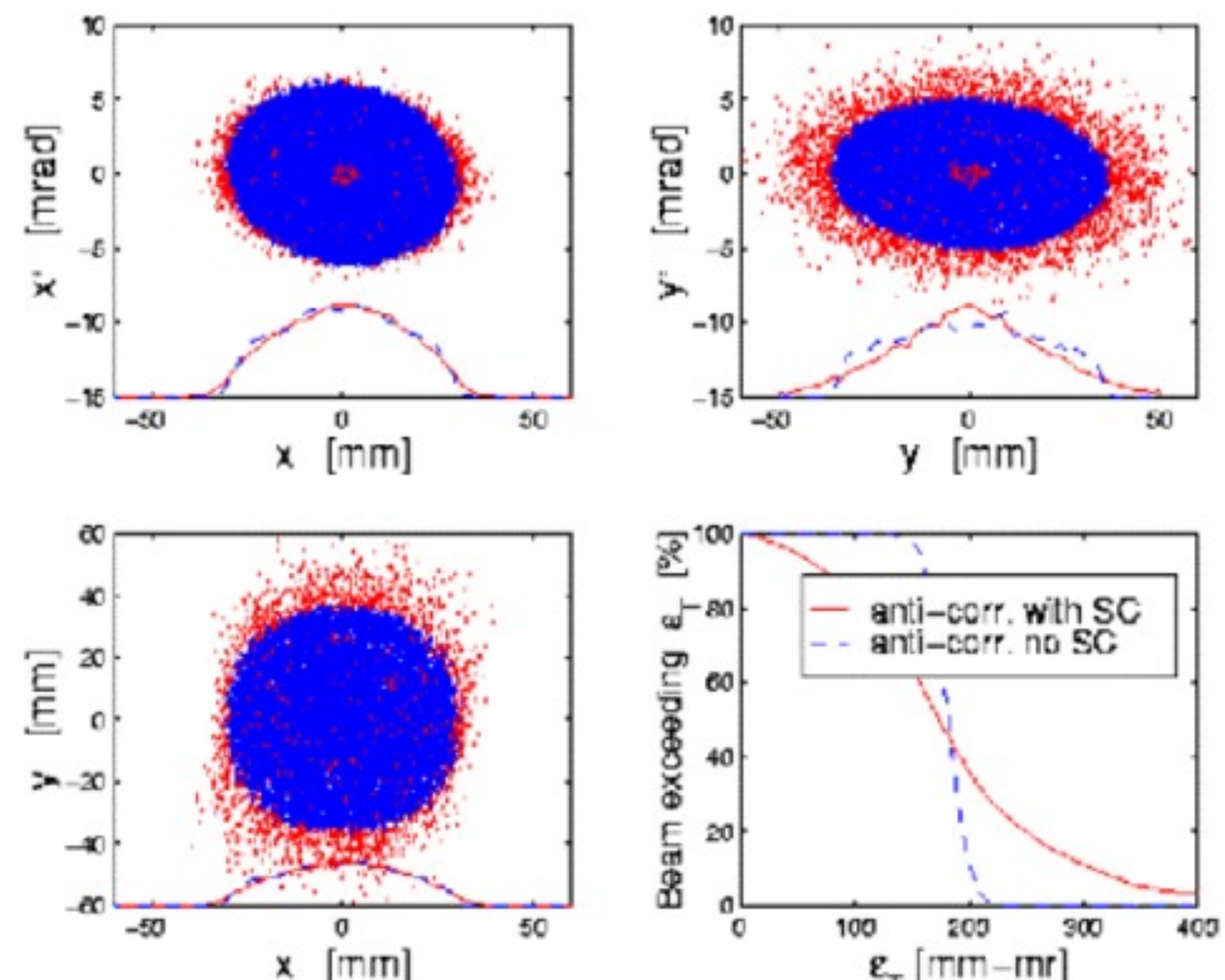
Space charge & halo formation (SNS)



Correlated painting with/ without SC

Anti-correlated painting with/without sc



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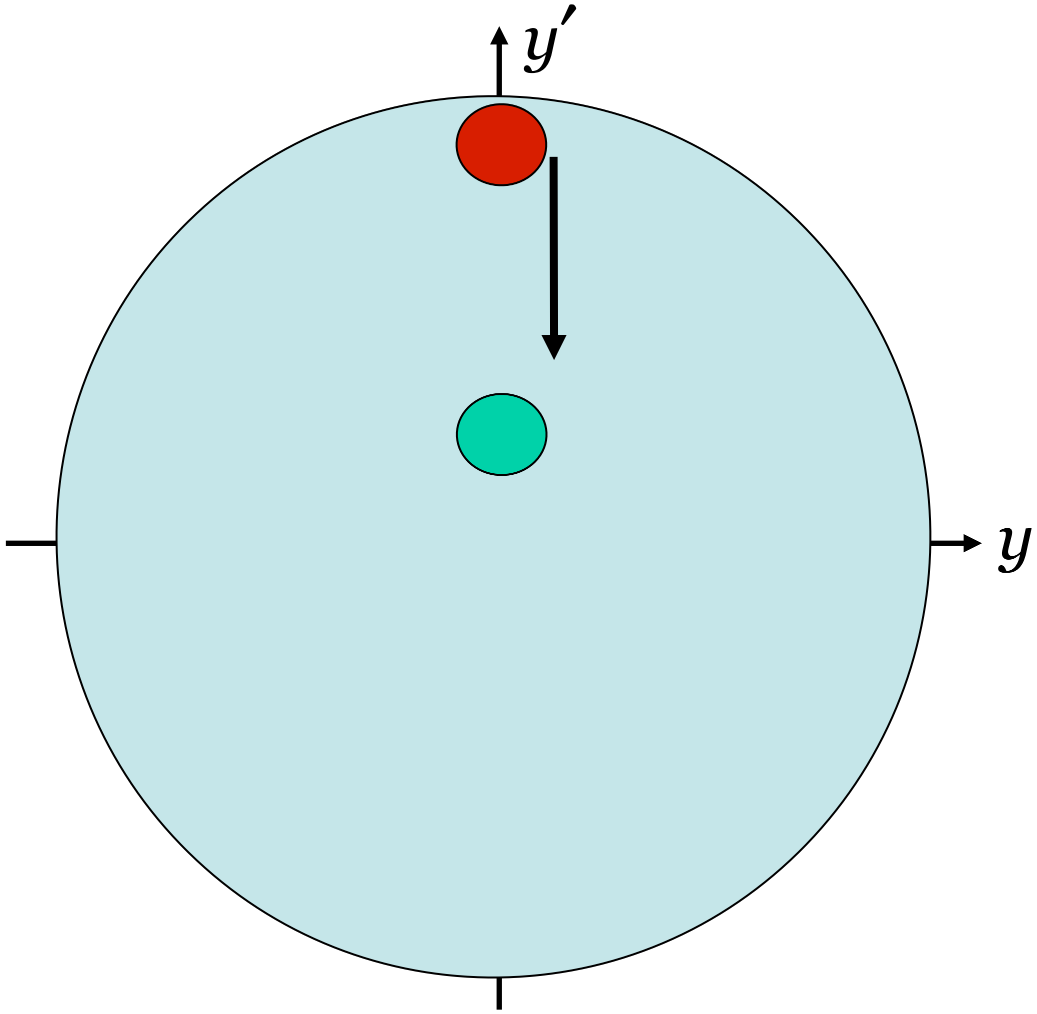
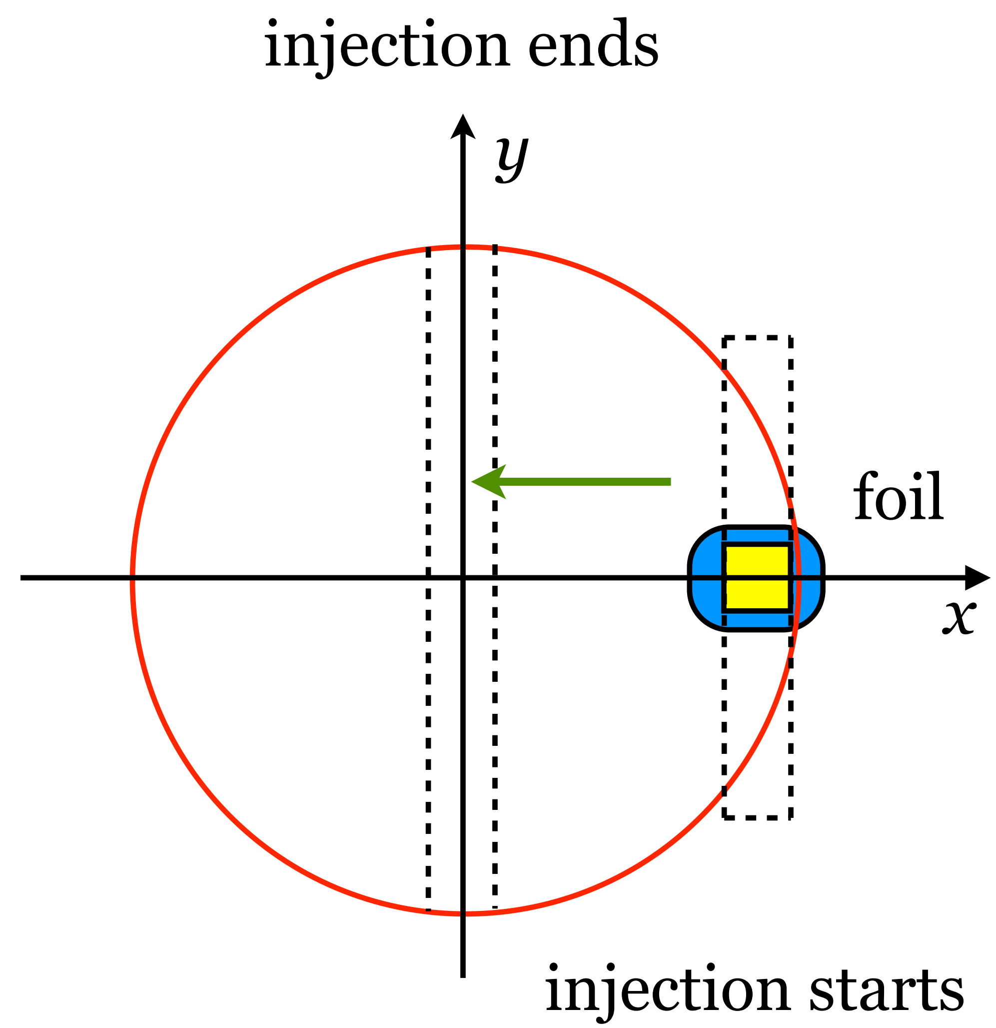
Vertical steering/horizontal painting

Steering in one direction, painting in the other





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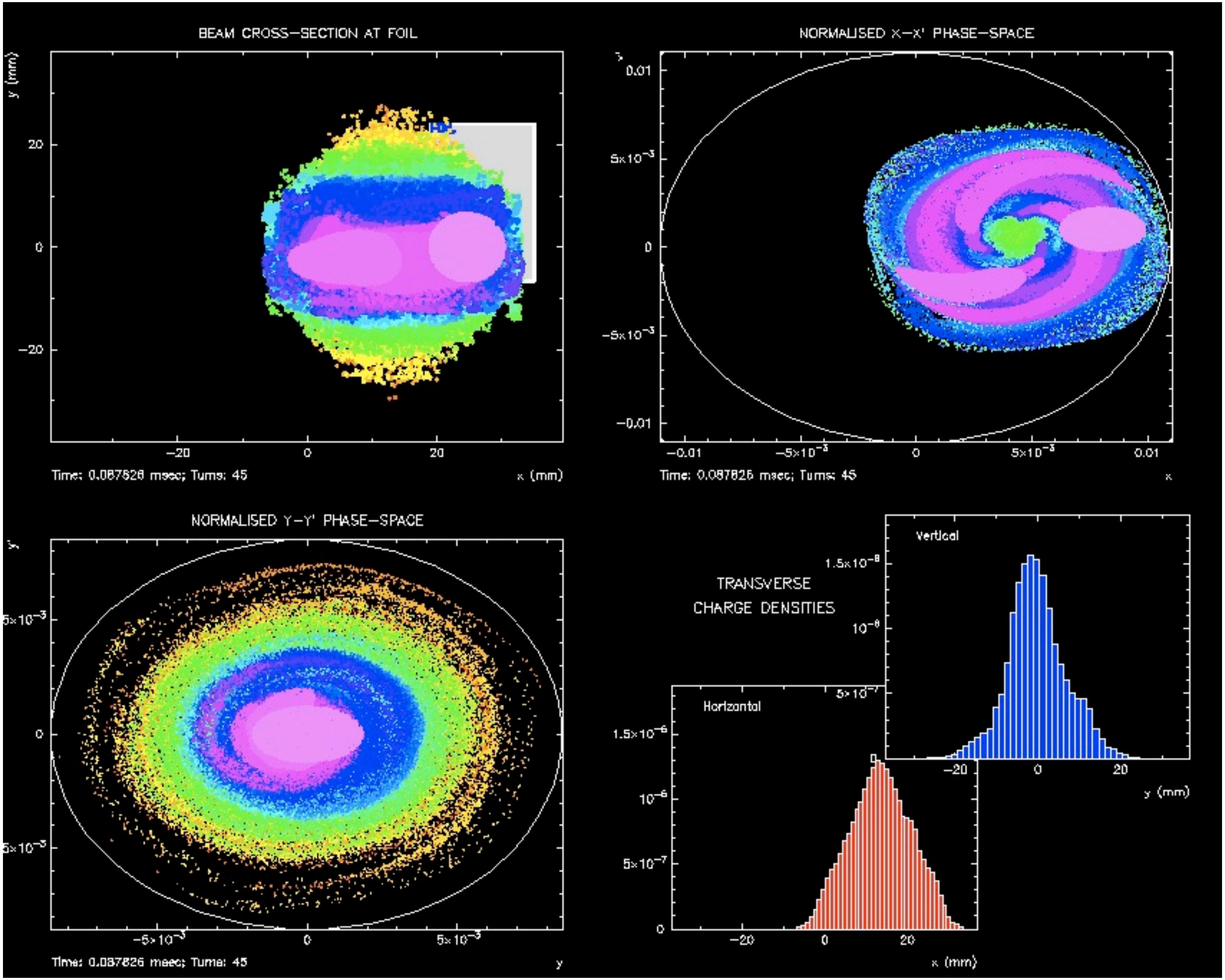
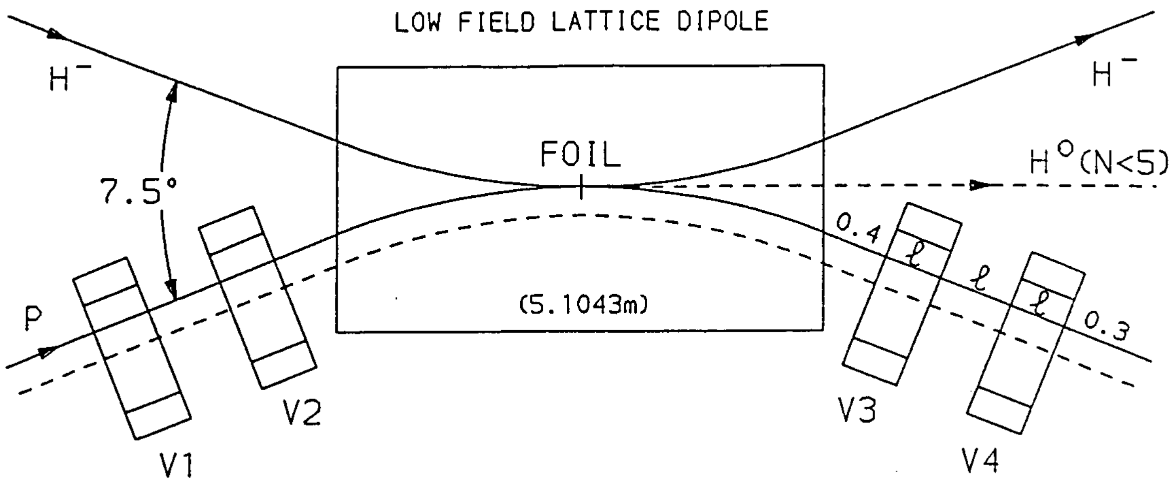
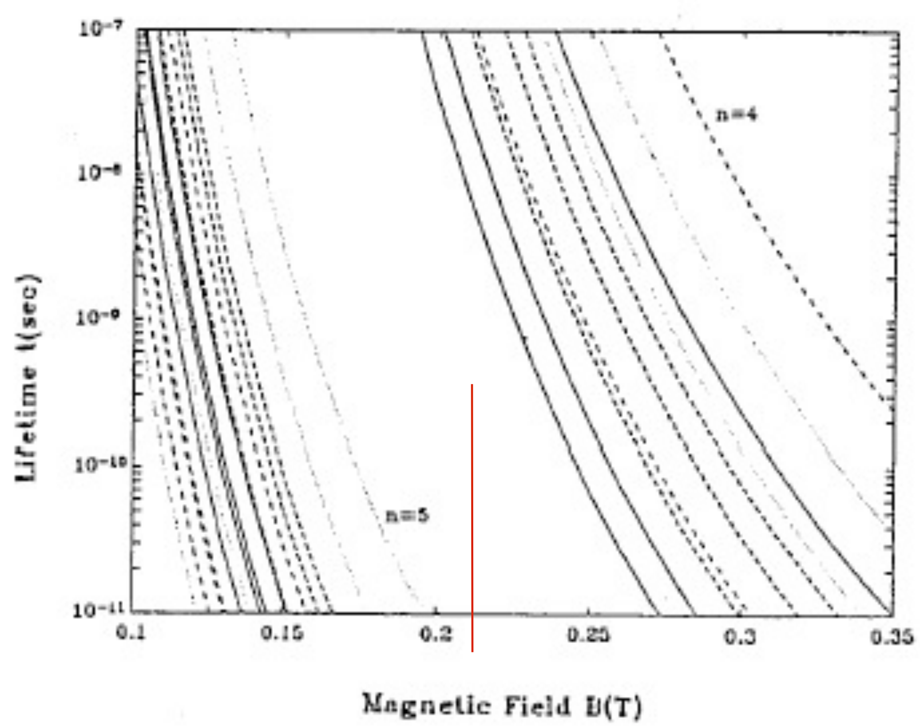
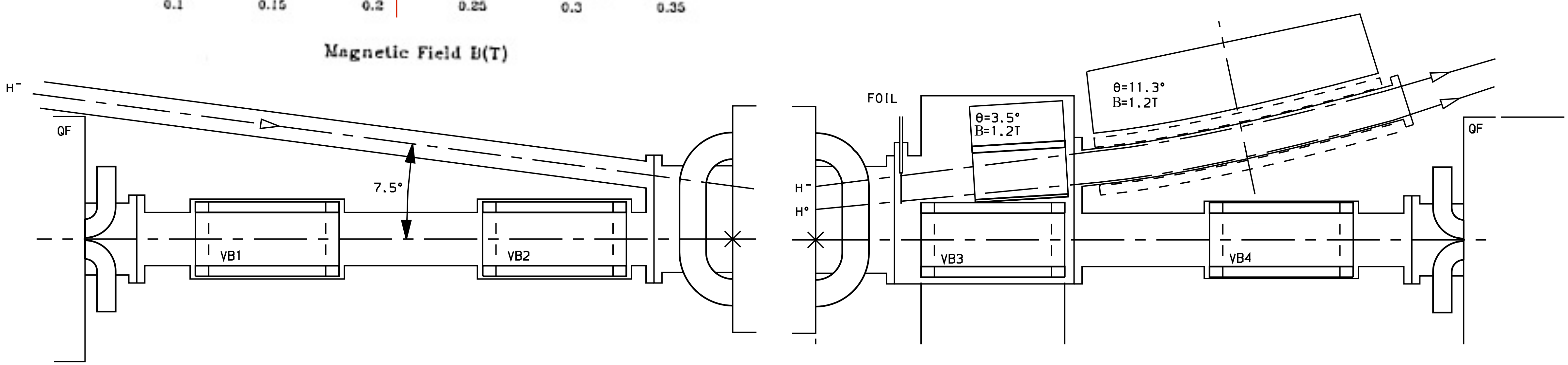

BEAM CROSS-SECTION AT FOIL
y (mm)
x (mm)
Time: 0.087826 msec; Turns: 45
NORMALISED X-X' PHASE-SPACE
x'
x
Time: 0.087826 msec; Turns: 45
NORMALISED Y-Y' PHASE-SPACE
y'
y
Time: 0.087826 msec; Turns: 45
TRANSVERSE
CHARGE DENSITIES
Vertical
y (mm)
Horizontal
x (mm)

Injecting into a Dipole





- Inject in a low field dipole (must avoid pre-stripping)
- B-Field chosen for optimal handling of H^0 excited states
- Simple magnet layout, no complicated injection chicane
- Easy handling of unstripped and partially stripped beam and stripped electrons



Painting using Dispersion

- Programmed orbit bumps magnets for vertical painting
- Injection in a region of non-zero dispersion
- Vary energy of beam in injection line to create horizontal painting
  - If beam has momentum range $p_0 \pm \delta p$, ramp to $p_0 + \Delta p \pm \delta p$. Then particles oscillate about a centre in the range $D_x \left(\frac{\Delta p}{p} \pm \frac{\delta p}{p} \right)$
  - e.g. might ramp $\frac{\Delta p}{p} = \frac{\delta p}{p} \rightarrow 3 \frac{\delta p}{p}$
  - Achieved with two cavities, one adjusts energy, one corrects phase.

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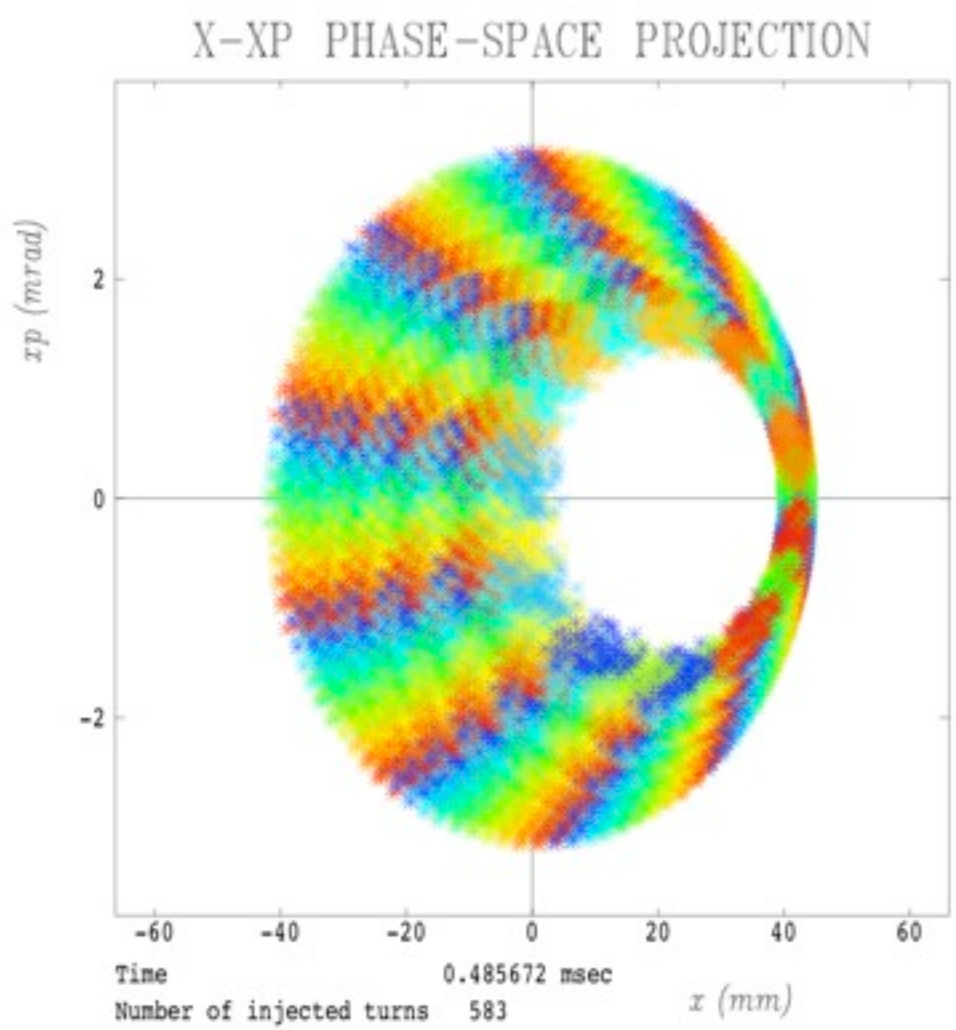

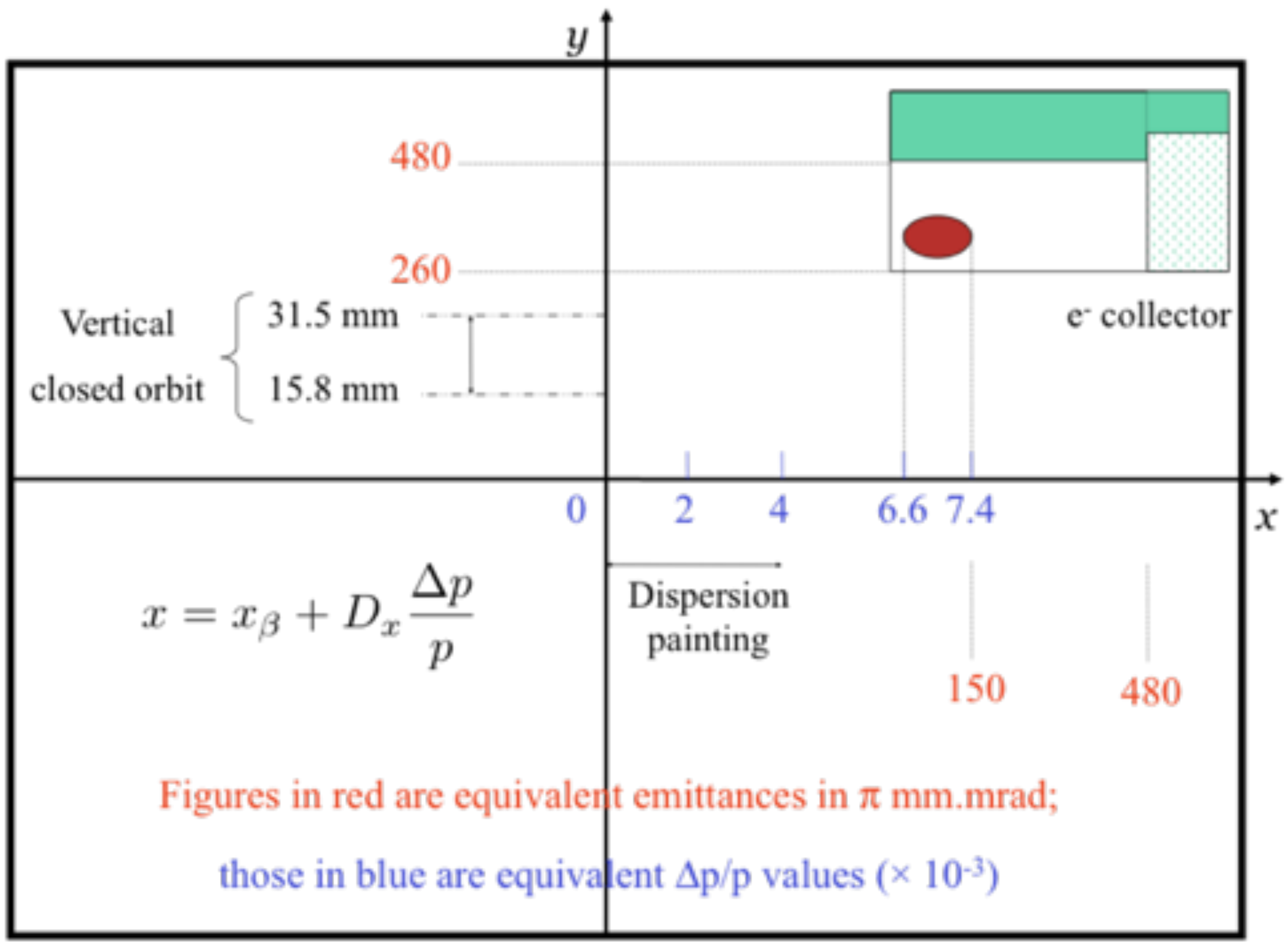

Horizontal painting via dispersion and energy/momentum ramping.

For momentum spread $\pm 5 \times 10^{-3}$, oscillation centre for particles starts in range $[0, 1]$ and ends in range $[3, 4]$.

Vertical oscillation centre reduces from 31.5 mm to 15.8 mm during in injection (painting an emittance of 150 mm.mrad), then reduces to zero as beam is pulled away from the foil to the centre of the machine.

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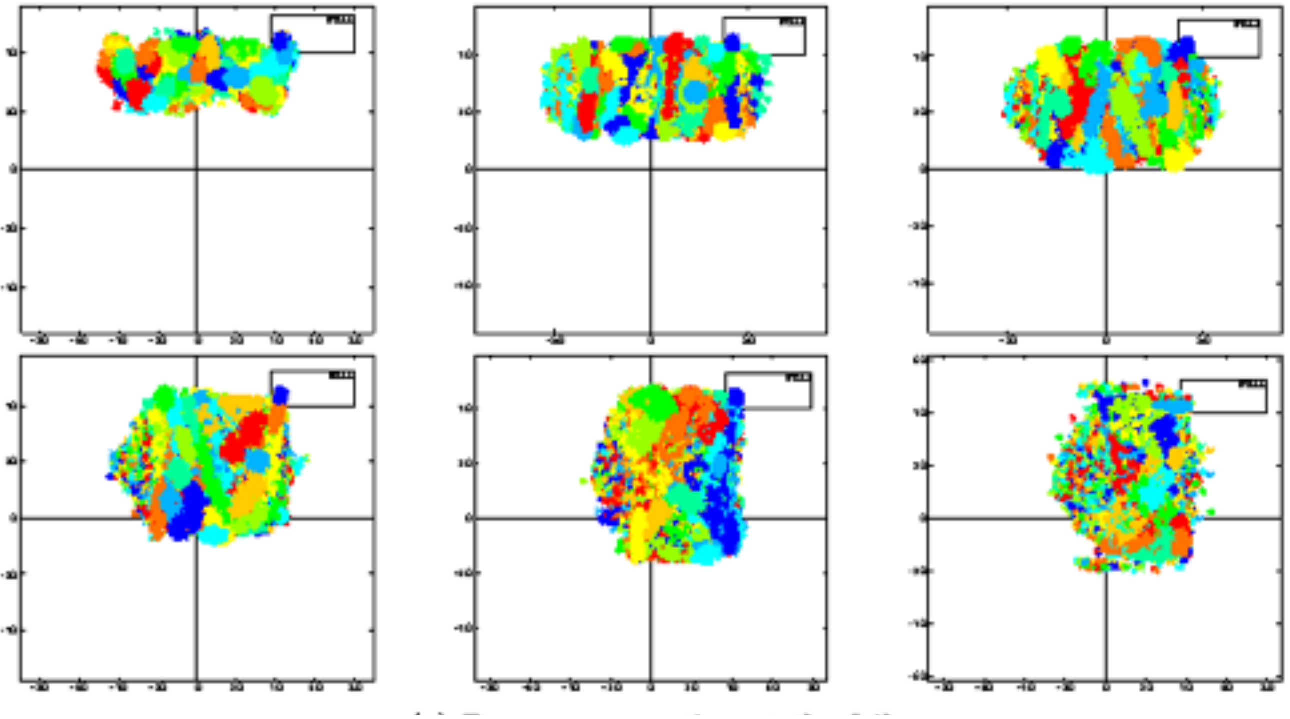
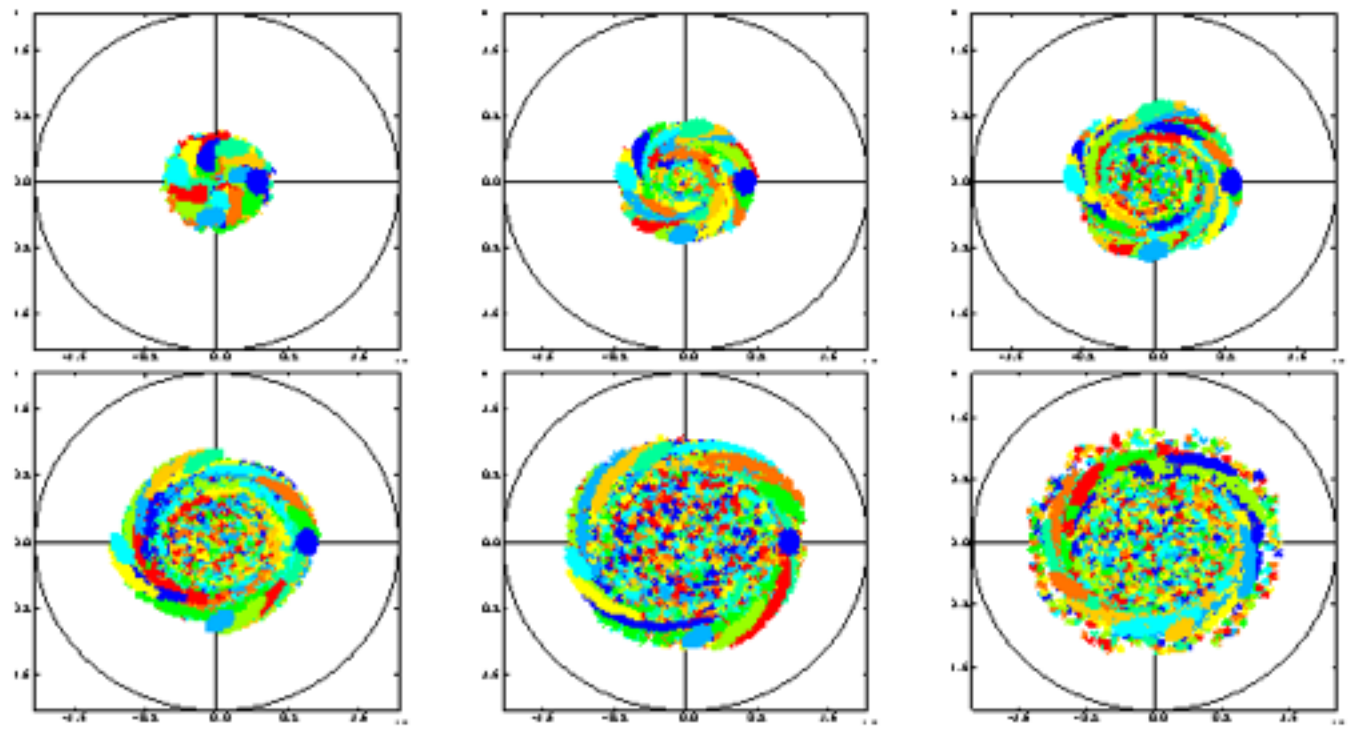
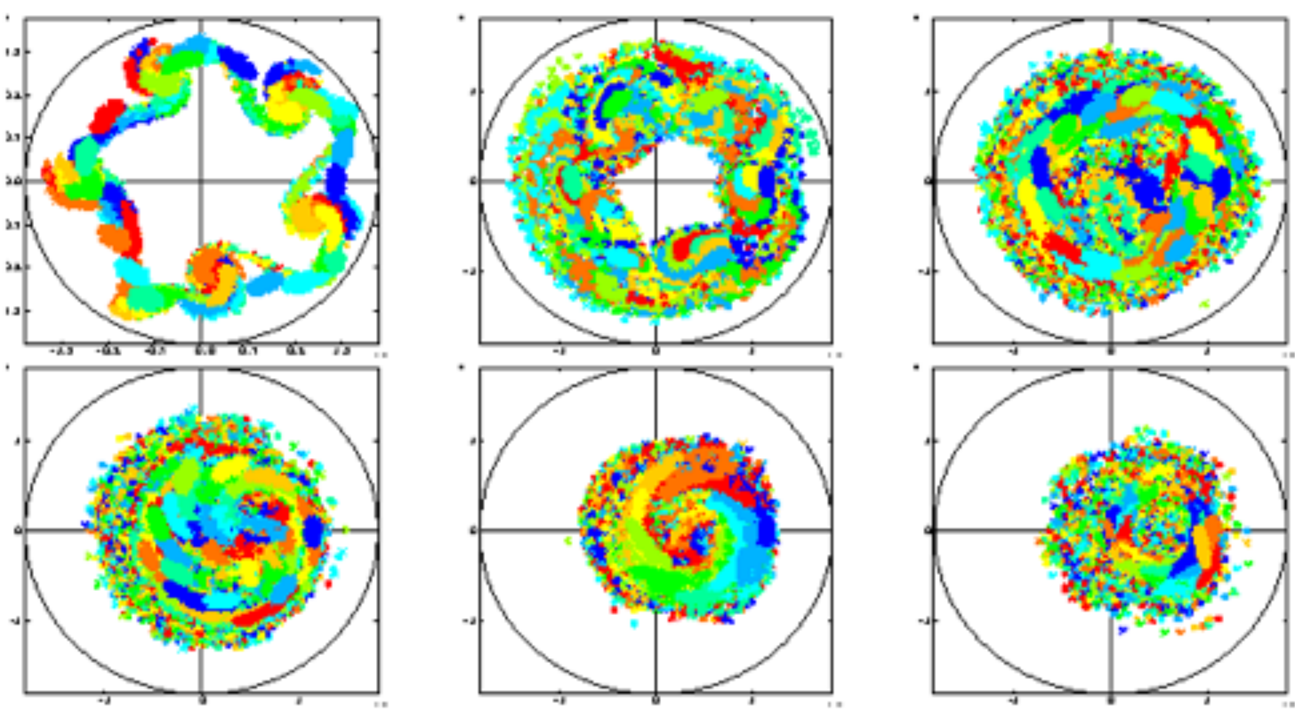


(a) Beam cross-section at foil



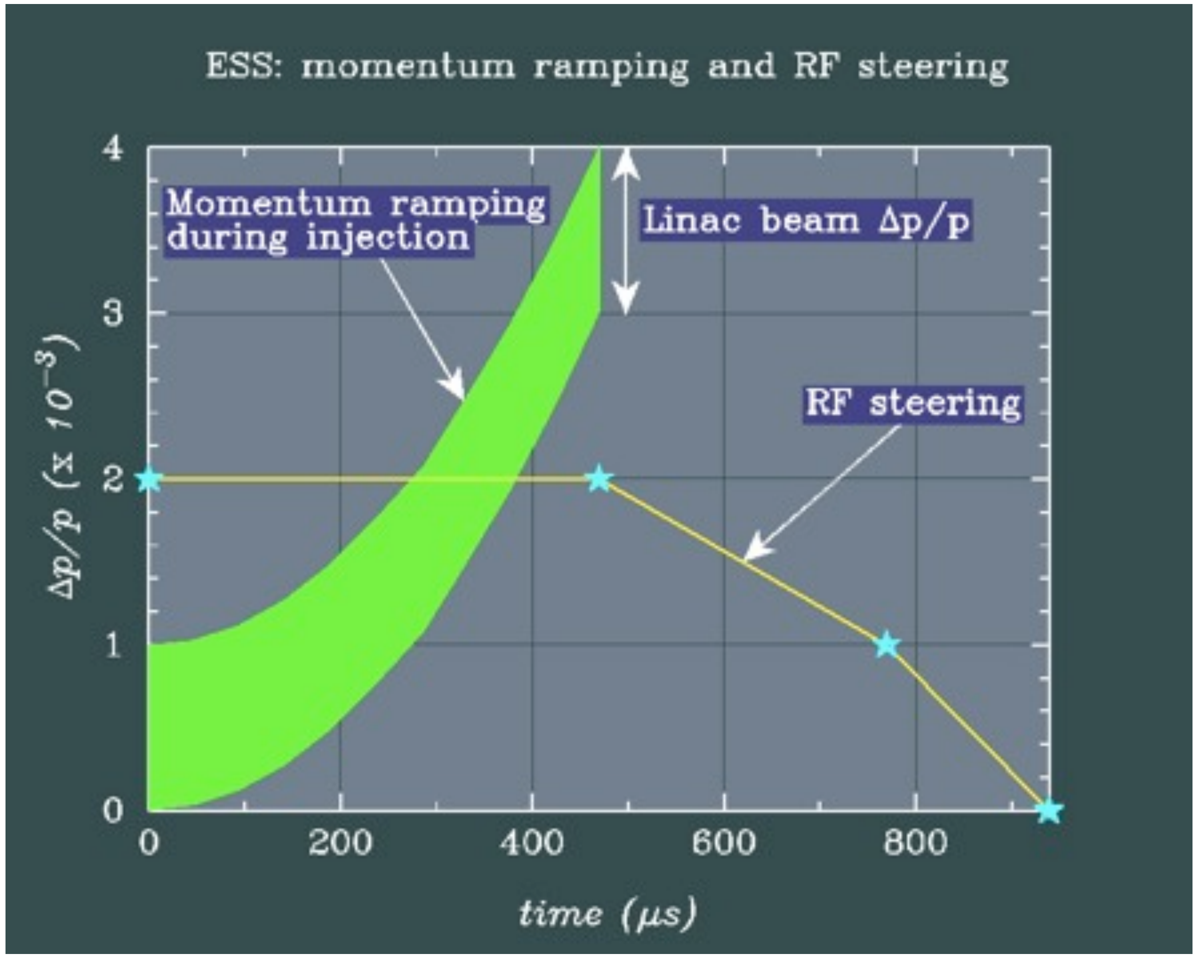
(c) Normalised vertical phase space

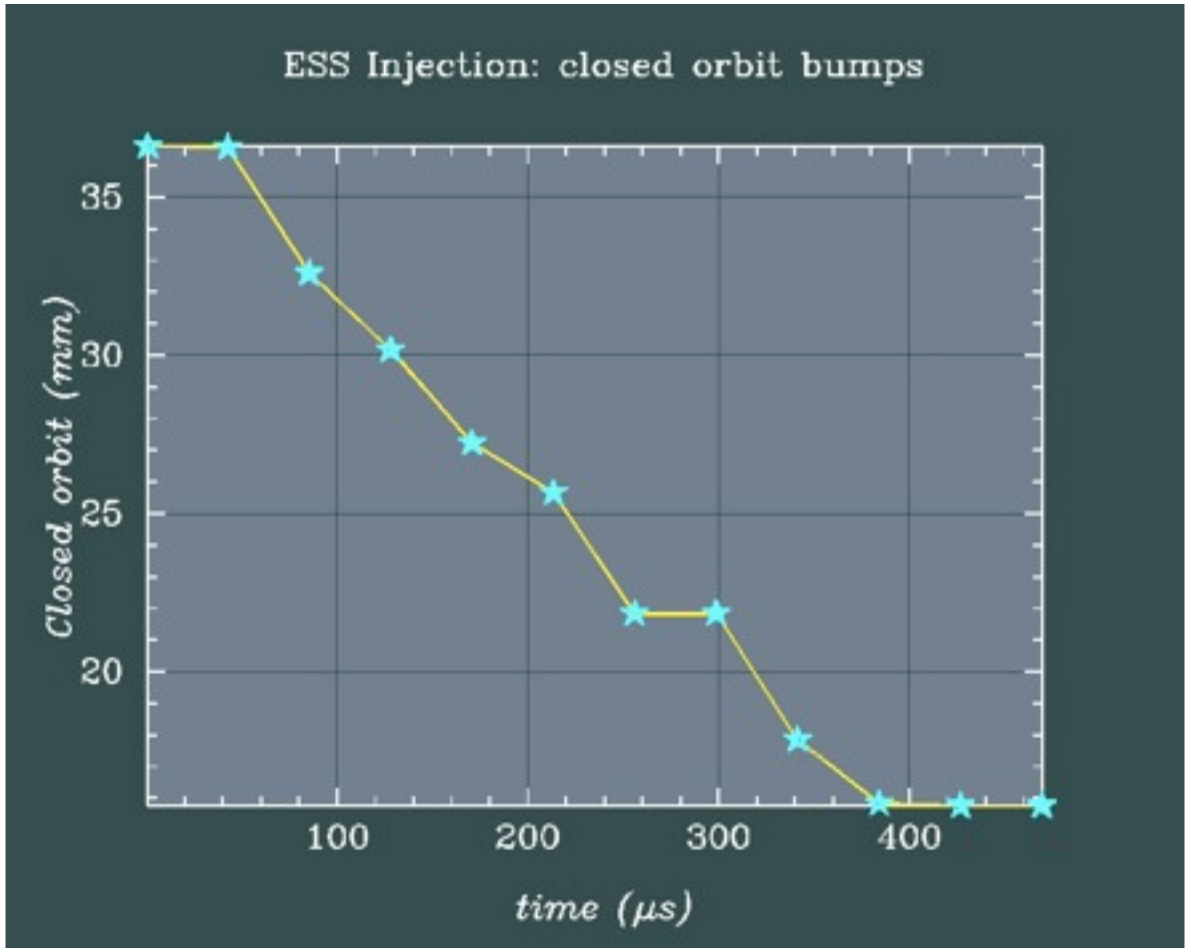


(b) Normalised horizontal phase space

Momentum Ramping and Vertical Orbit Bump

Example: ESS short pulse design 2002





Beam momentum spread $\pm 5 \; 10^{-4}$ is ramped [0,1] to [3,4] 10^{-3} during injection

Orbit bumps chosen to minimise foil hits by re-circulating protons

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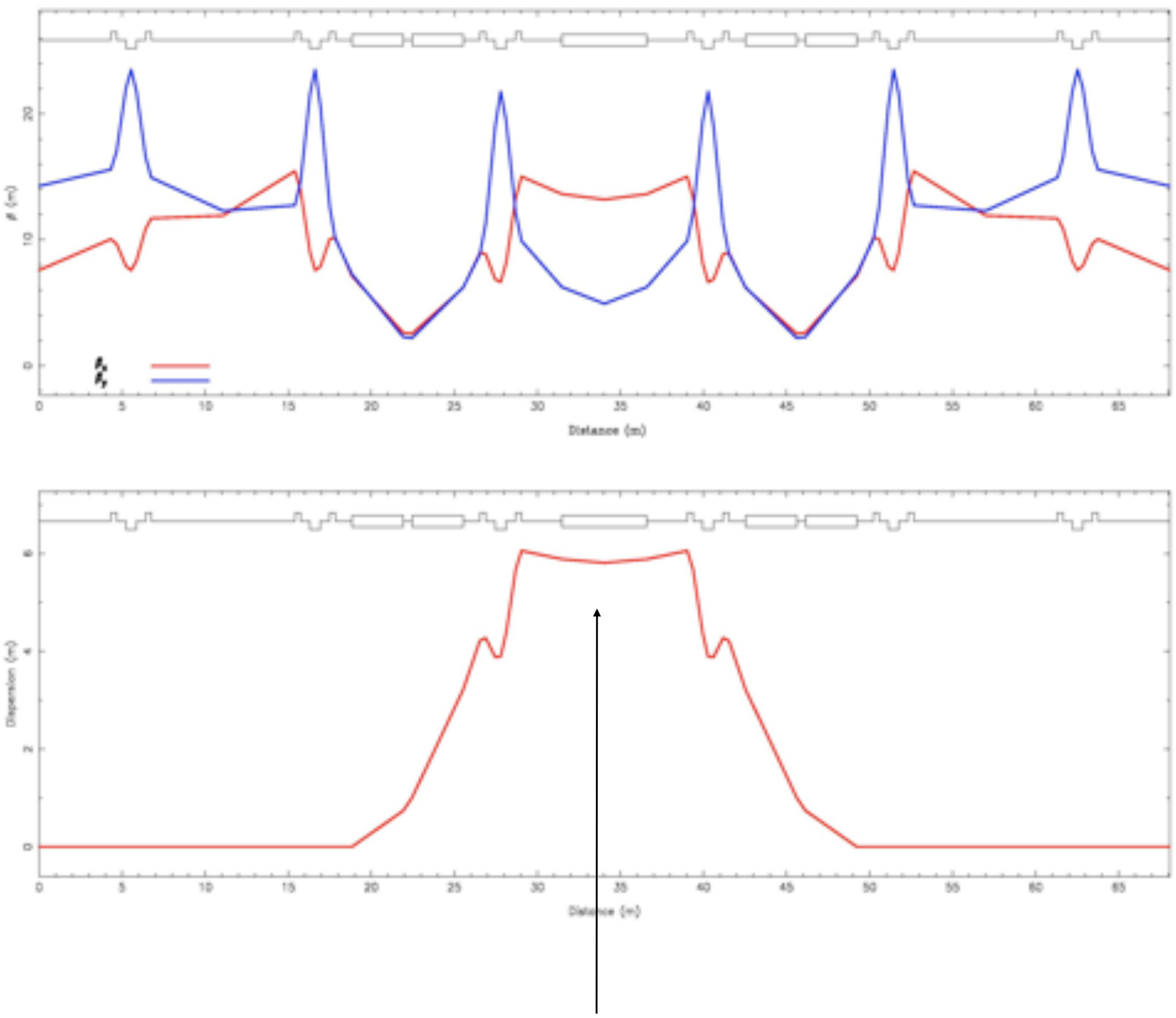
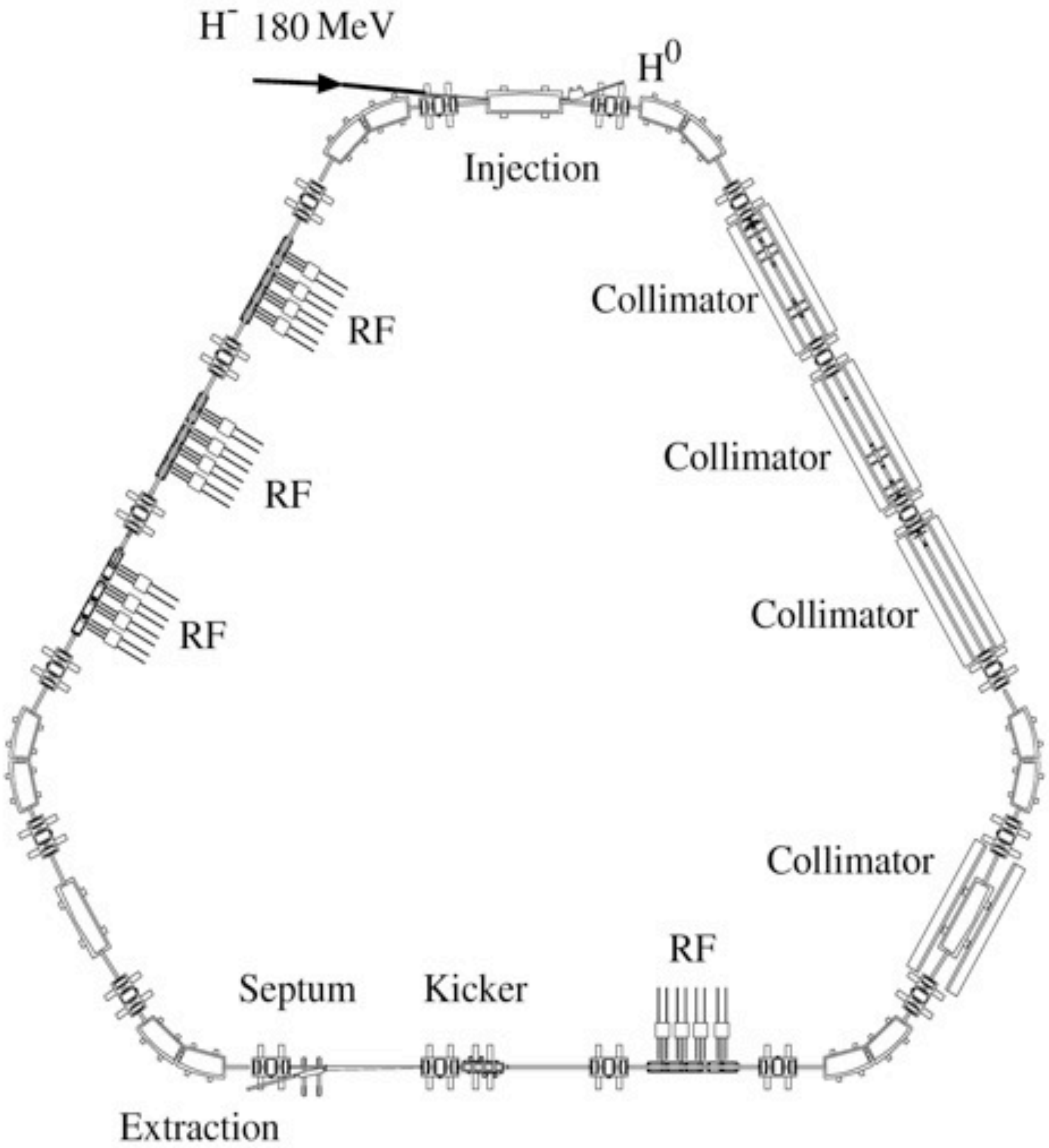
Dispersion Painting: Optics Requirements

Preferred value for normalised dispersion is $D_x/\sqrt{\beta_x} \approx 1.6$ in injection dipole





Problem - how to paint different distributions

Consider an axisymmetric beam density distribution in normalised η-η' phase space during multiturn injection.

Define $\rho^2 = \eta^2 + \eta'^2$ and let $\lambda(\rho)$ be the particle density at radius ρ.

What is the closed orbit as a function of time needed to realise:

(i) A uniform distribution in phase-space inside a radius R during a total injection time of t_{max}?

(ii) A Gaussian distribution $\lambda(\rho) = \dfrac{N}{2\pi\sigma^2} \exp\left(-\dfrac{\rho^2}{2\sigma^2}\right)$ where the injection is performed during a time $0 < t < t_{max}$?

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Solution

Suppose particles are injected at a steady rate N/t_{max}. Then

$$2\pi\lambda(\rho)\rho\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{N}{t_{max}}.$$

(i) for a uniform distribution, $\lambda = \dfrac{N}{\pi R^2}$, this integrates to

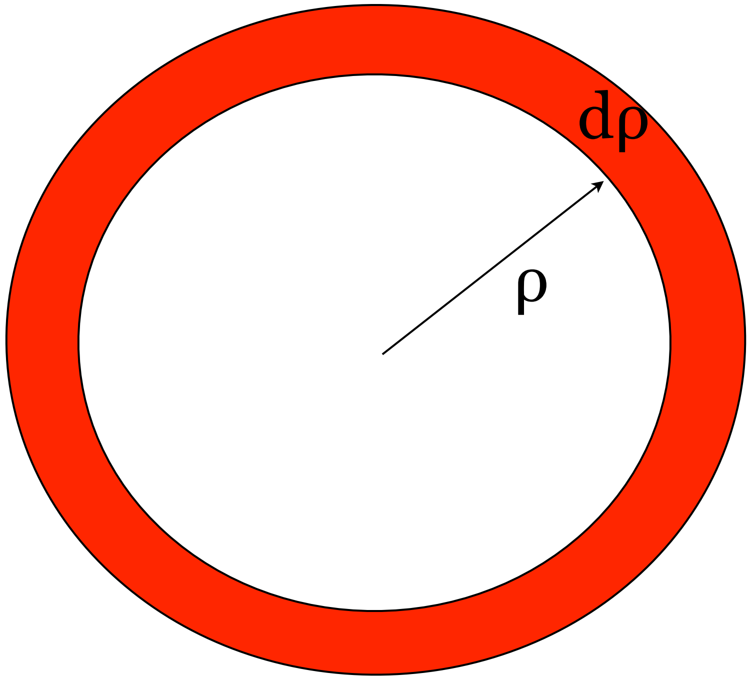
$$x_0 = R\sqrt{1 - \frac{t}{t_{max}}}$$

(ii) for $\lambda = (N/2\pi\sigma^2)\exp(-\rho^2/2\sigma^2)$, we obtain

$$-N\exp\left(-\frac{\rho^2}{2\sigma^2}\right)\Bigg|_0^{x_o} = N\frac{t}{t_{max}}$$

giving

$$x_0 = \sigma\sqrt{2}\sqrt{-\ln\left(1 - \frac{t}{t_{max}}\right)}.$$



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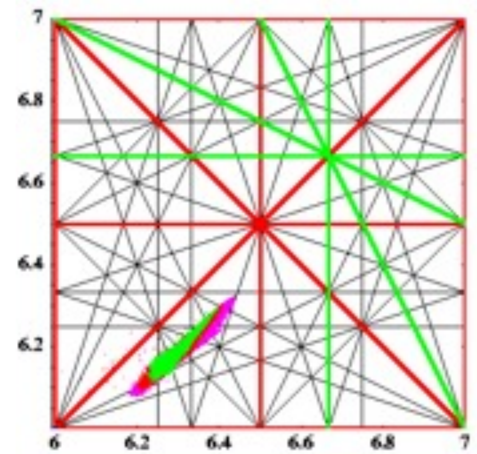
Further Charge-Exchange Injection Considerations

- Circulating protons can pass through stripping foil. Need to minimise the foil traversals.
  - SNS averages about 6 hits per ring proton over 1000 injection turns; ESS was optimised to $\lesssim 1$.
- Foil hits lead to heating and high temperatures, shortening foil life.
  - Need quick disconnect system, easy replacement.



- Careful control of closed orbits and painting
- Ring lattice tunes Q_x, Q_y can be critical
  - Space charge tune depression and tune spread can result in fourth order space charge resonances and destroy the beam

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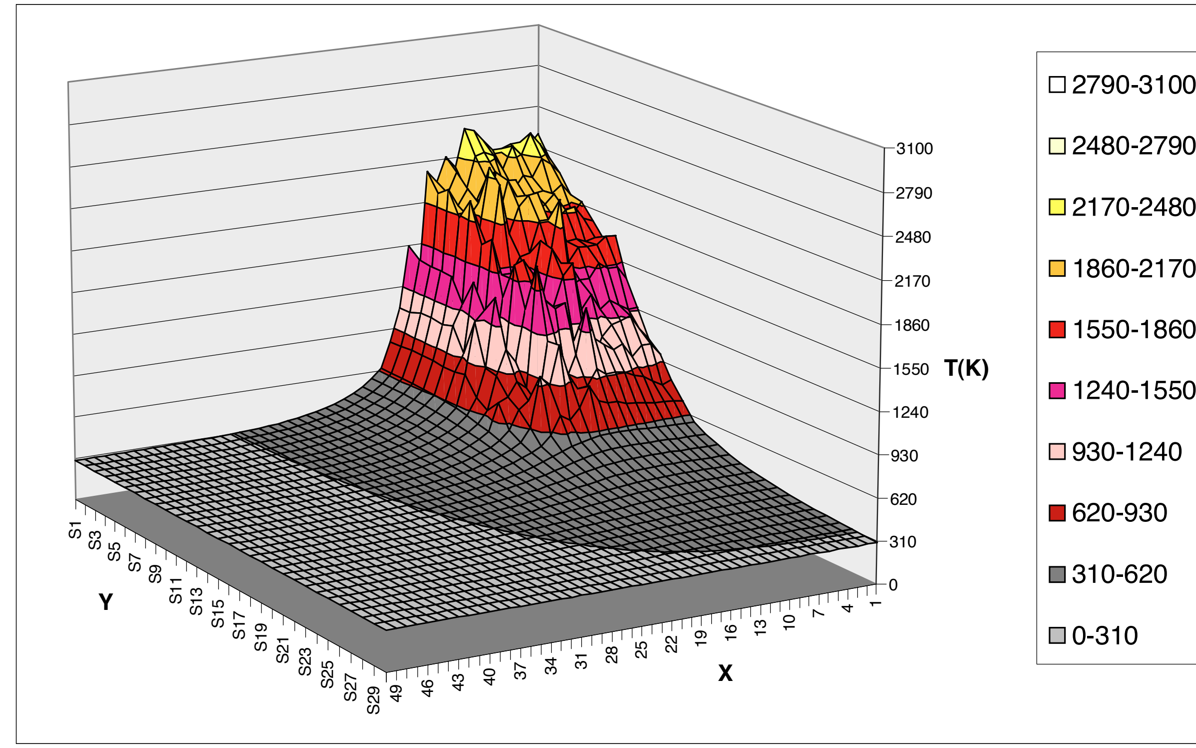
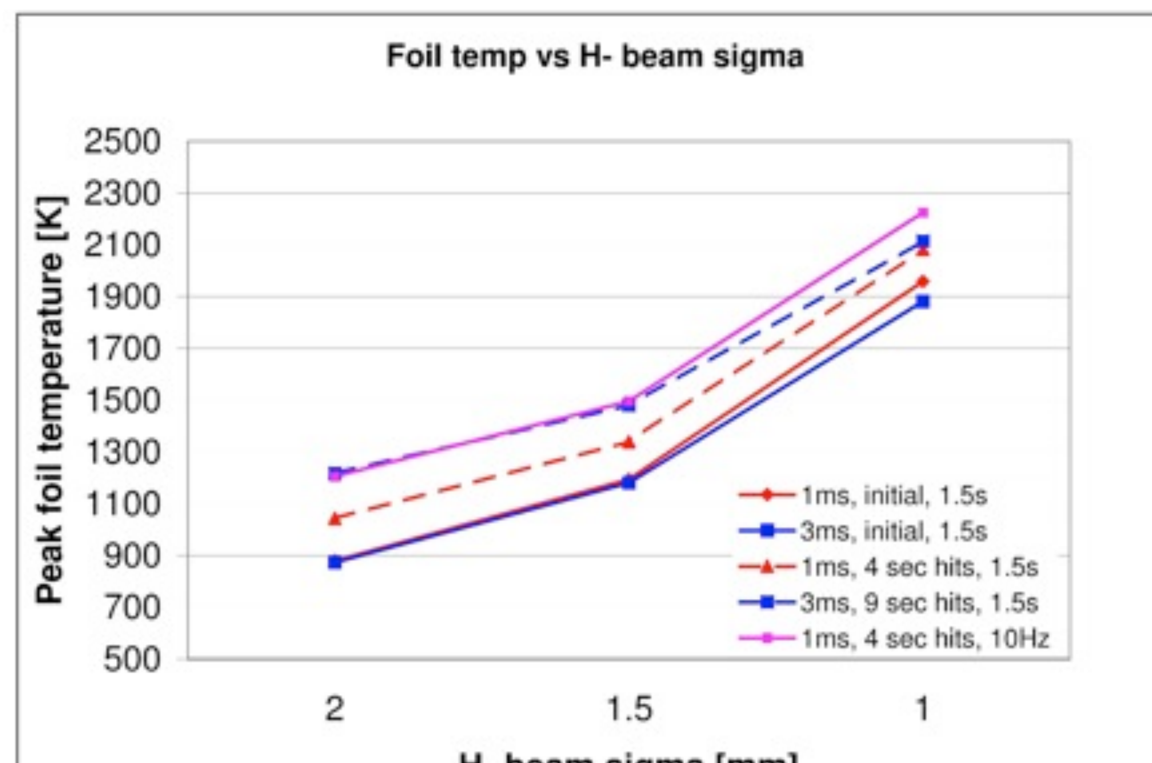
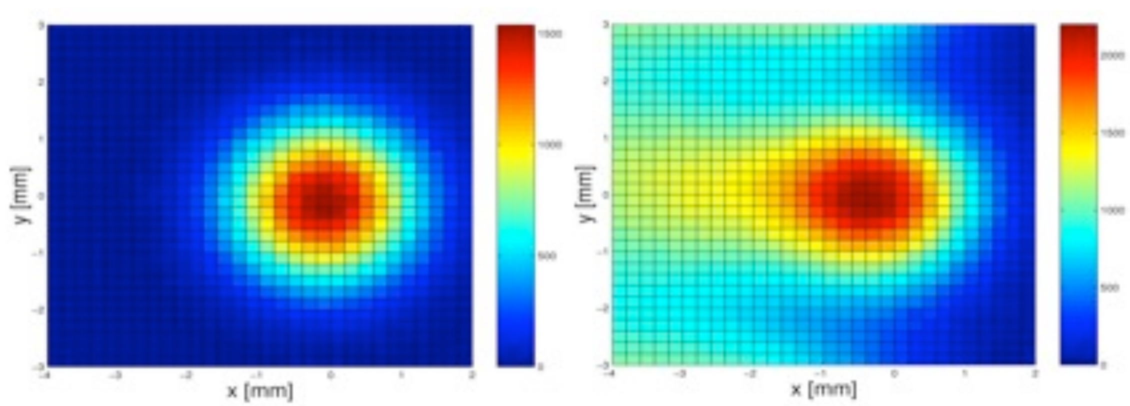
Foil Heating

- Peak temperature strong function of linac beam size
- Peak temperature depends on number of secondary hits (Project-X predicts 9 for 270 turn injection)
- Peak temp ~ 2000 K (Graphite)
- Radiation cooling between pulses
- Peak reached for ESS after 7 pulses.





Temp vs beam size

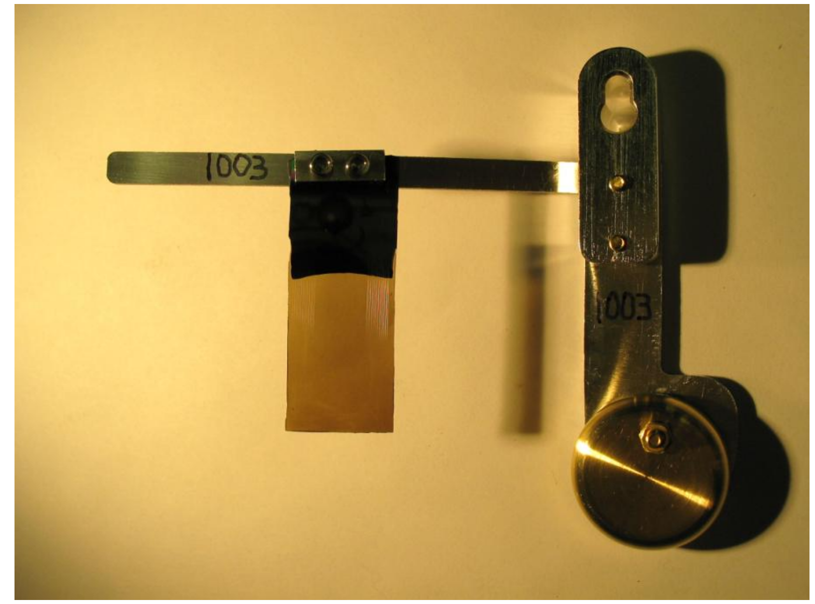


Temp due to linac beam only, included secondary hit

Stripping Foils

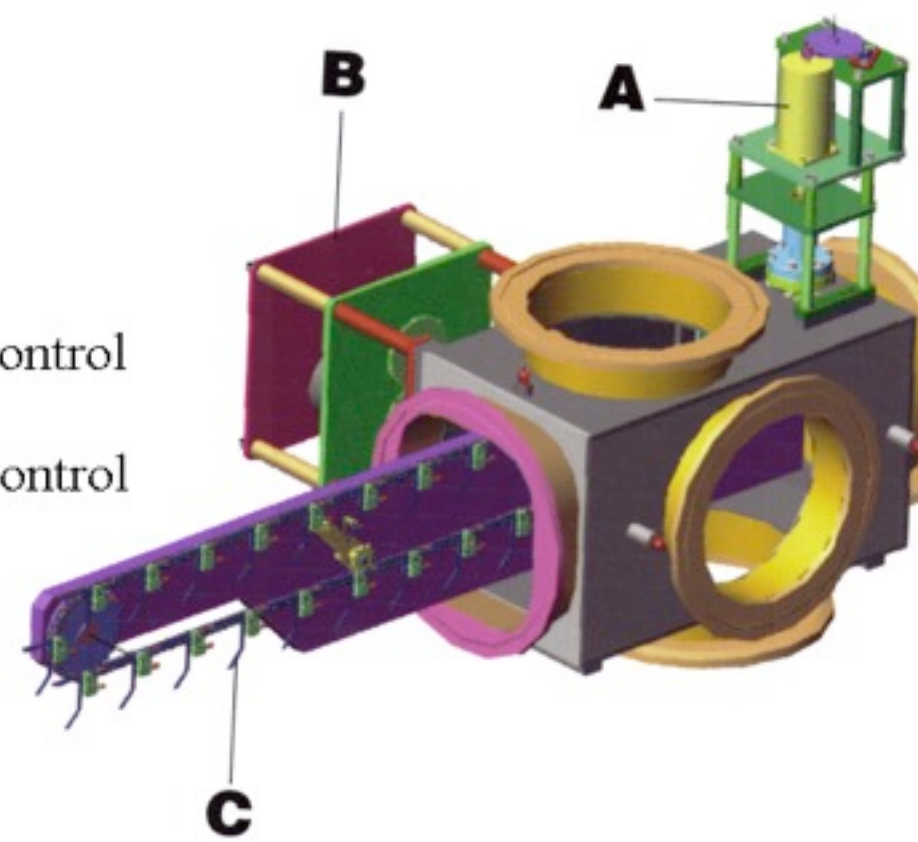
Typical foil:

- Nano crystalline diamond on Silicon substrate
- 0.350 μg/cm^2
- 17 mm wide, 45 mm tall
- (25-35 mm free standing height)



Foil failures:

- Vacuum breakdown (arcing) caused by charge build up, due to secondary electron emission (SEM) and thermionic electron emission
- Reflected convoy electrons striking the foil
- Beam halo hitting Si substratte
- Sudden beam excursions, causing beam to hit Si substrate
- Eddy current heating
- Normal operation – foil gets too hot



A. Foil insertion control

B. Foil changing control

C. Foil holders

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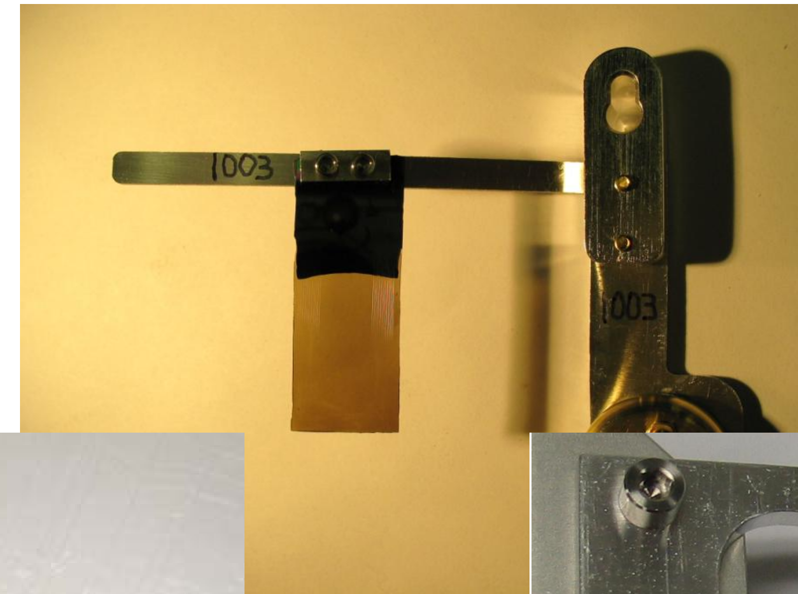

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hot

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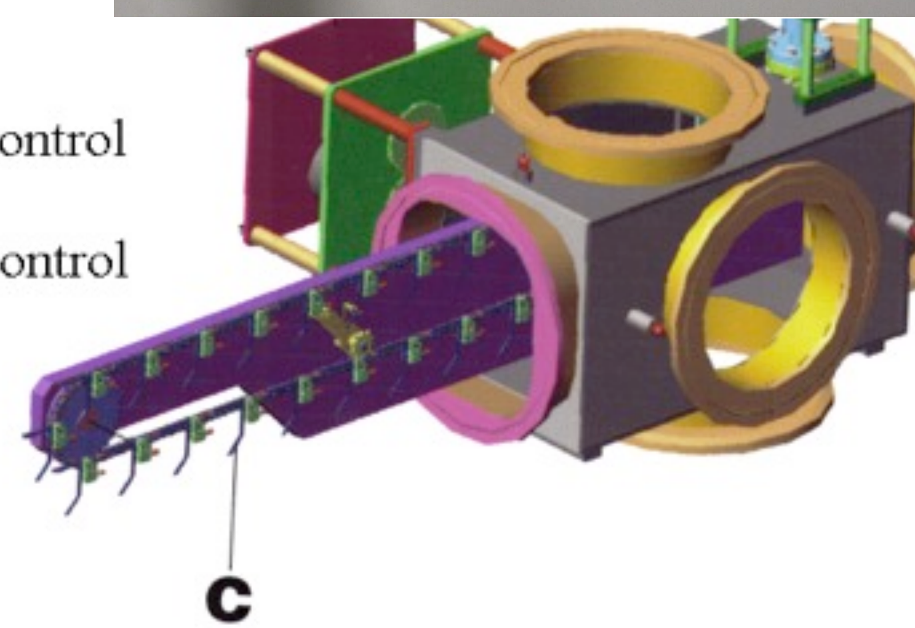
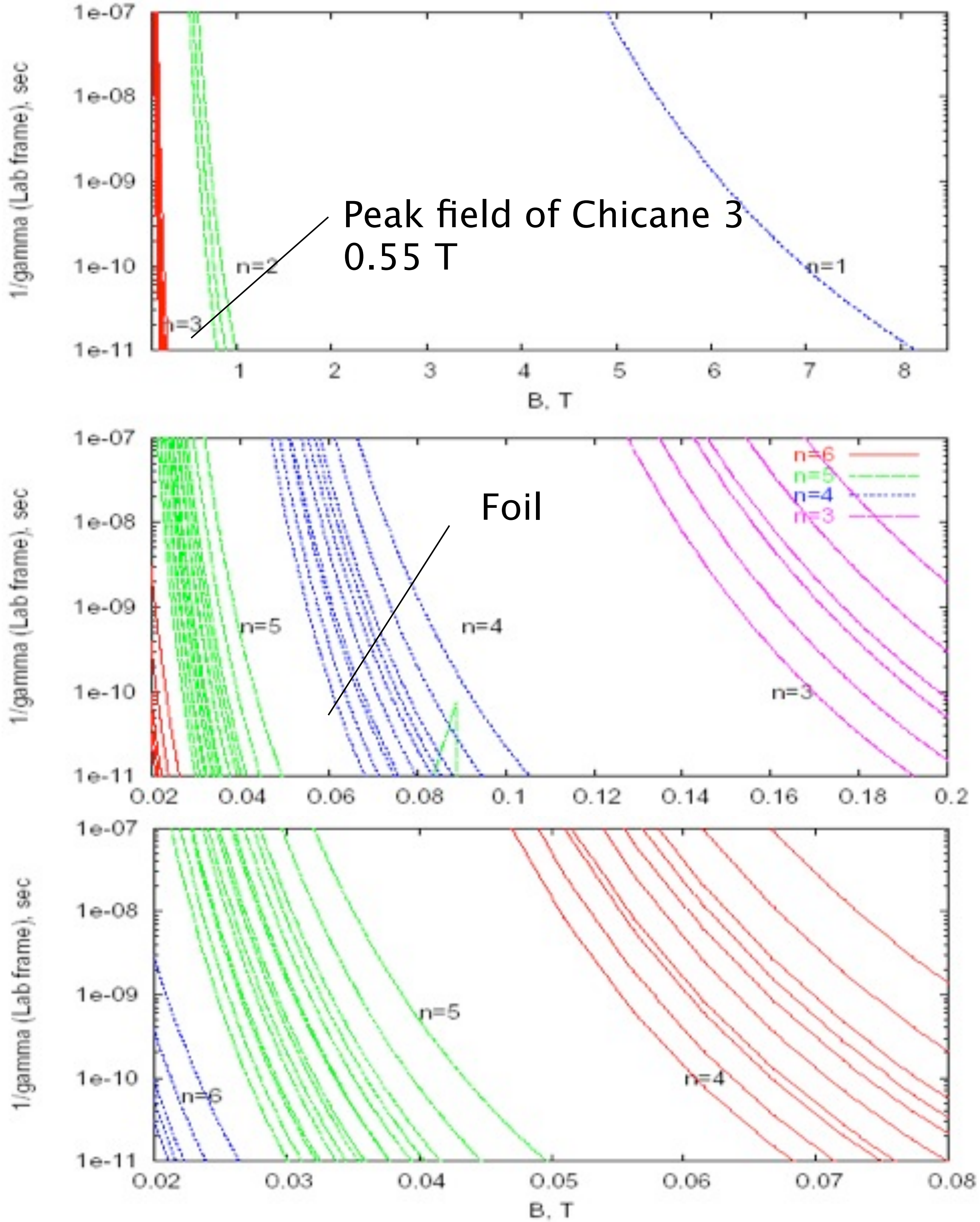


Lifetime of Stark States (Project-X)



- Missed H^- will be stripped in 5 mm
- N=5 and higher strip immediately
- N=4, 10 mm, $\Delta\theta$=30 μr
- N=3, 80 mm, $\Delta\theta$=150 μr
- N=1,2 will be stripped by second foil

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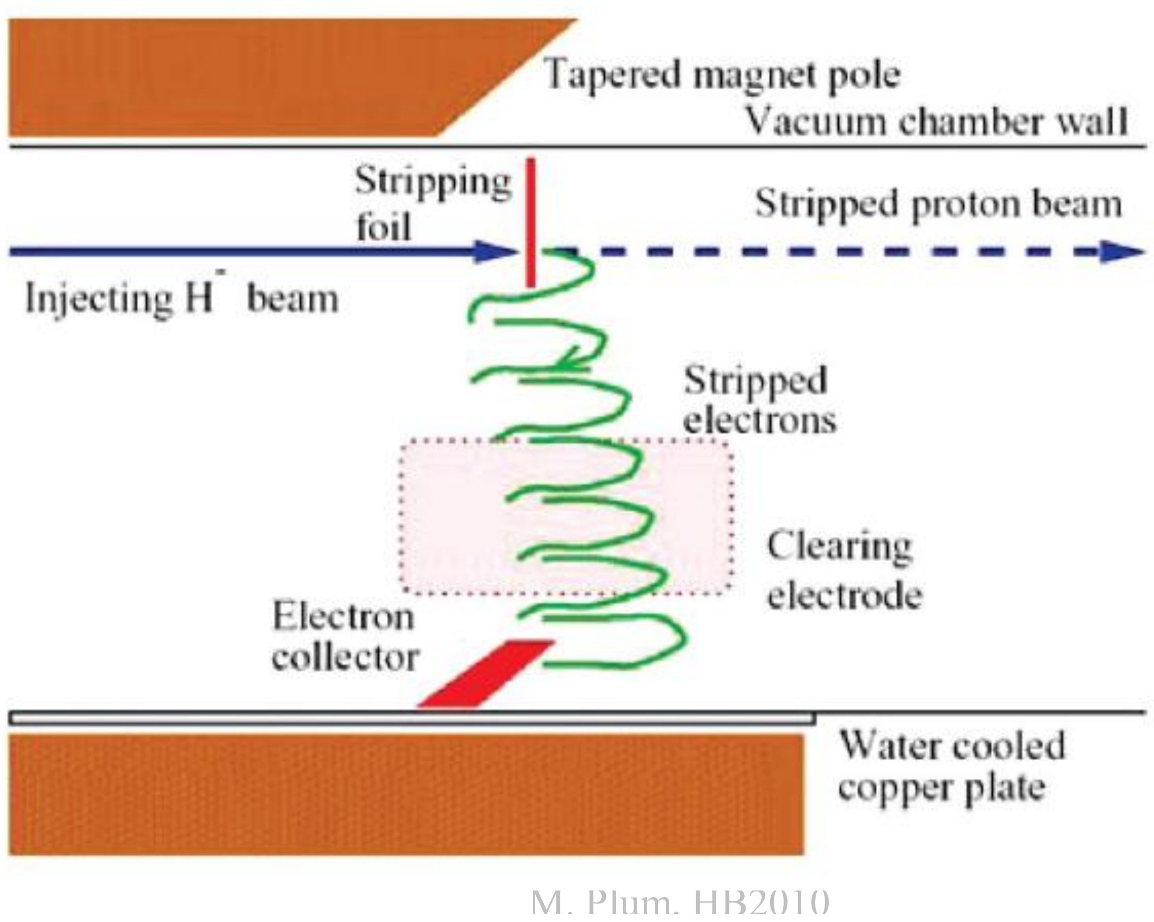
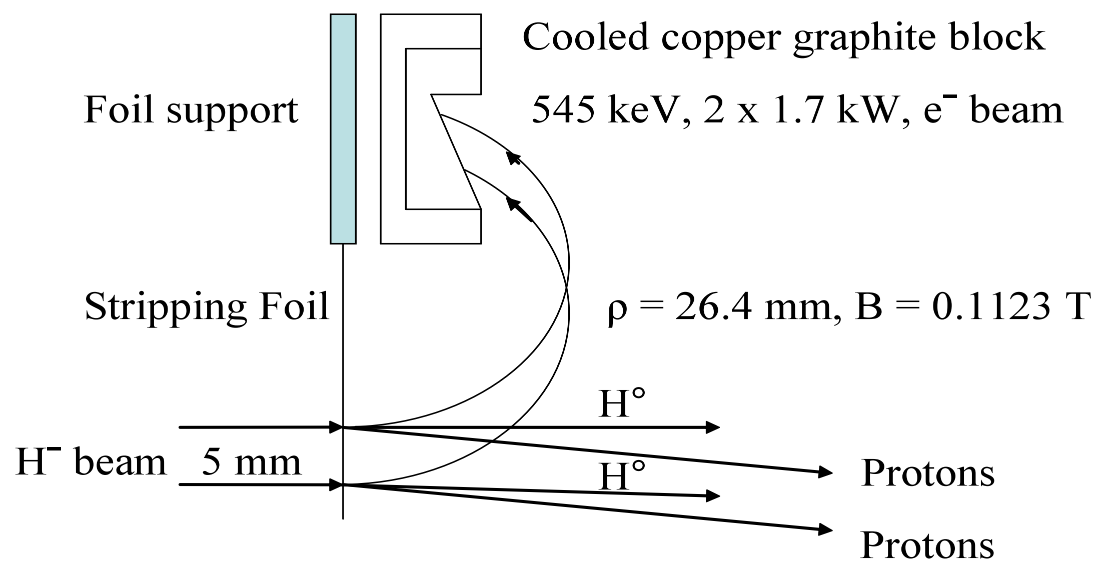
Electron Collection





SNS electrons spiral down to vacuum chamber floor in magnetic field created by tapered magnet pole

When injection is in a dipole, electrons are bent in the dipole field onto a water-cooled catcher, part of the foil support.

Painting scheme comparison

Scheme	Advantage	Disadvantage
Correlated	Paint over halo (square beam profile)	Singular density Coupling emittance growth
Anti-correlated	Ideal uniform distribution Immune to coupling (circular beam profile)	Halo growth due to space charge Extra 50% aperture
Coupled (correlated)	Paint over halo (diamond beam profile)	Extra acceptance needed
Paint (H) / steer (V)	Similar to anti-corr. Paint Less fast kickers	Foil support difficult suscep. to operational error
Paint (V) / steer (H)	Similar to anti-corr. Paint Less fast kickers	Vertical injection suscep. to operational error
Oscillating bump	Uniform distribution Paint over halo	Fast power supply switch Extra 50% aperture (H&V)

What happens if you choose the wrong tune:

Zero current

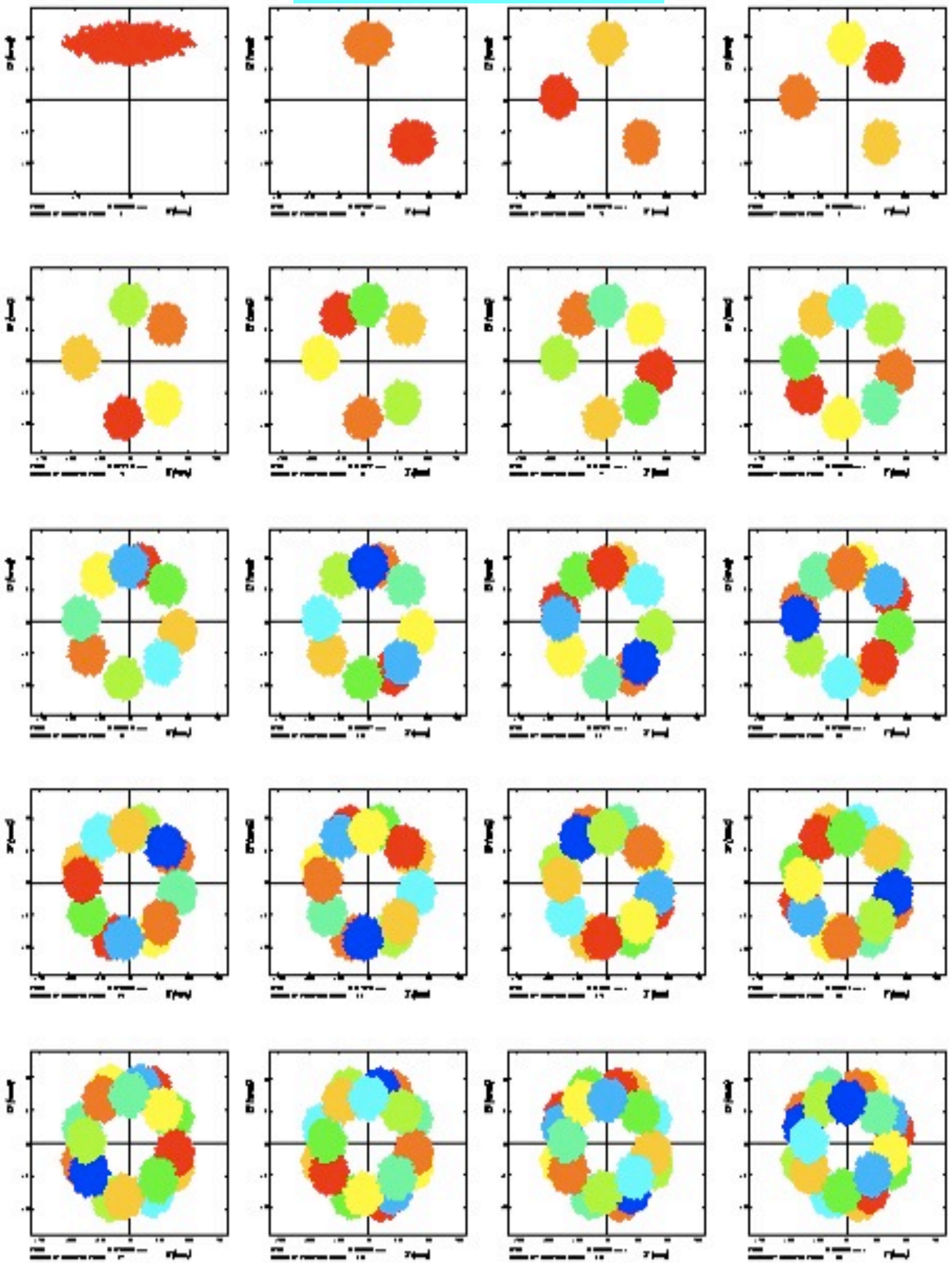


Figure 1: Vertical phase space (no space charge)

With space charge

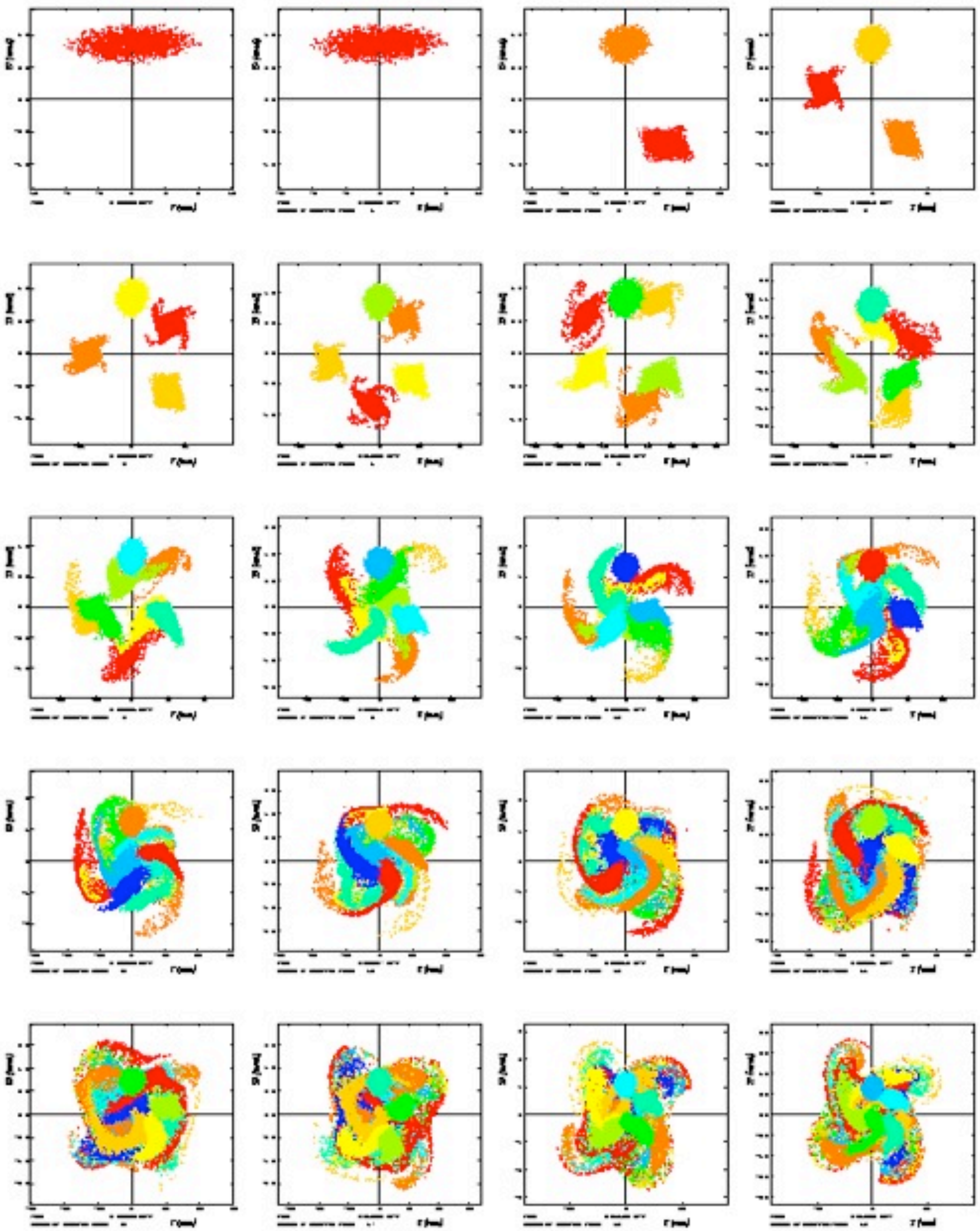
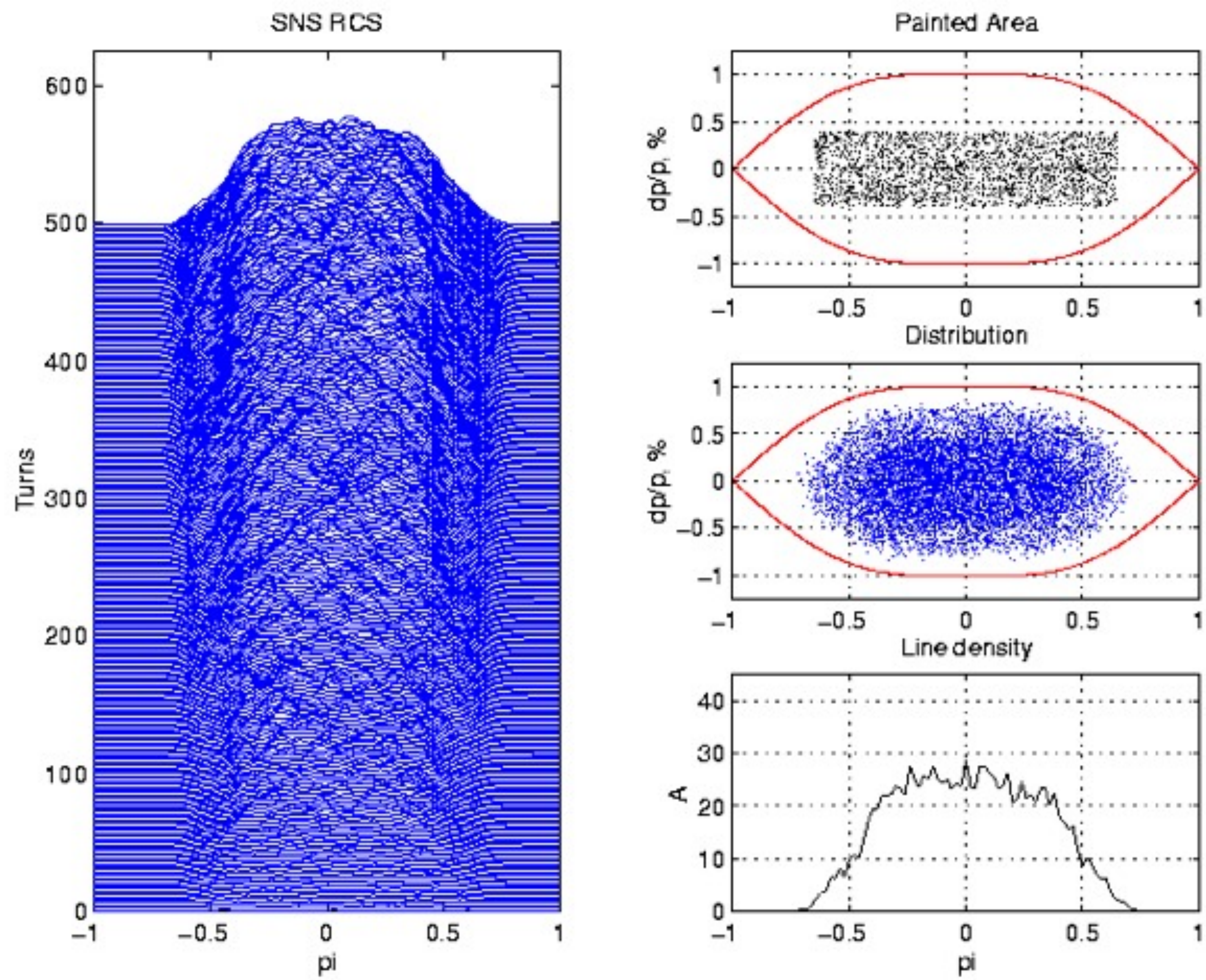


Figure 1: Vertical phase space (with space charge)

Longitudinal painting

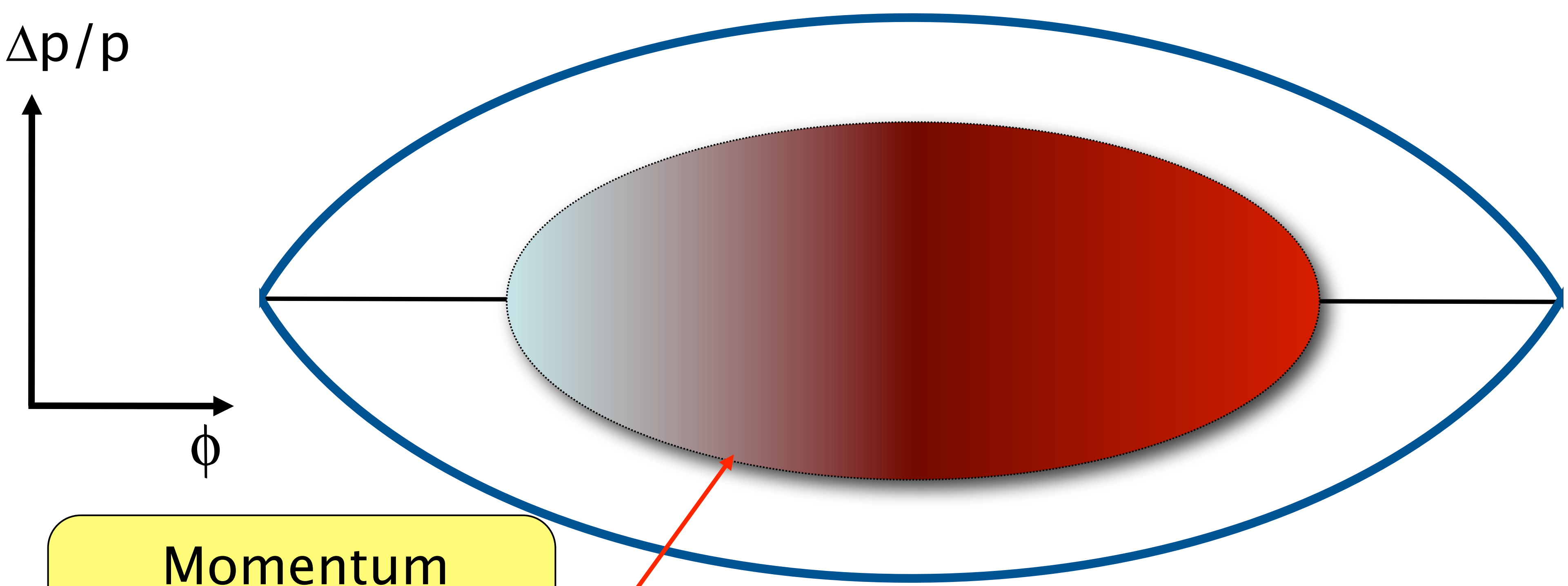
- Clean longitudinal halo from beam in achromatic arc before injection
- Paint the momentum space by modulating the injecting beam energy
- RF steering
- Modulate RF voltages
- Use dual harmonic/barrier buckets



Longitudinal Phase Space Gymnastics

RF Voltage modulation controls bucket height

Aim for good bunching factor to reduce transverse space charge effects



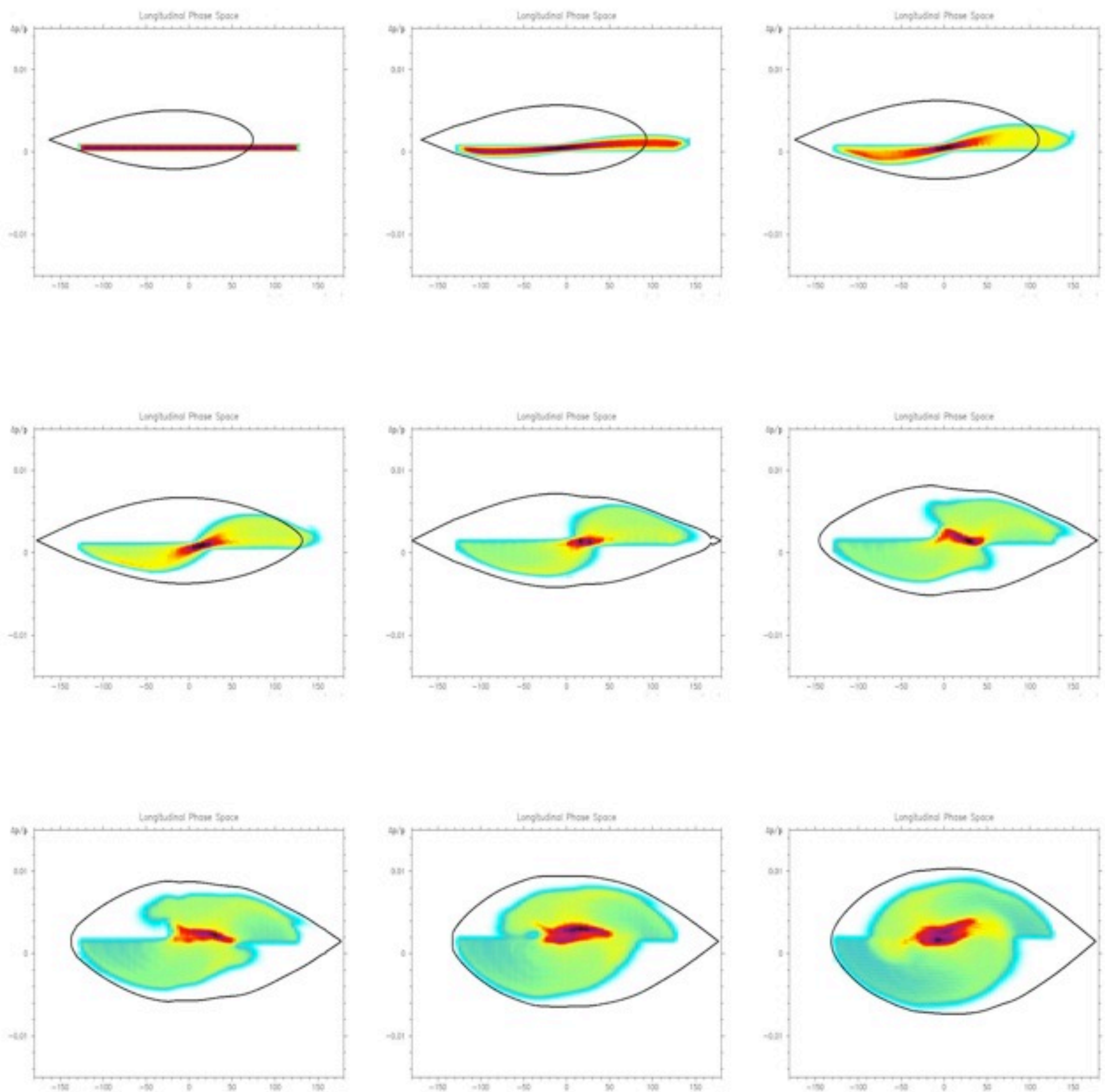
RF steering moves central axis of bucket up and down with respect to nominal ring energy

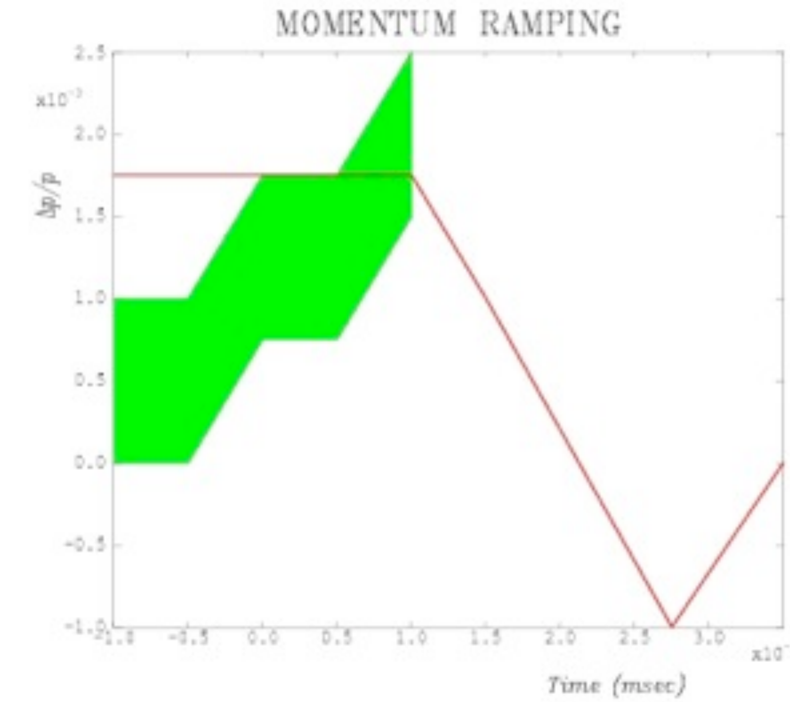
Momentum ramping in the injection line varies (vertical) position of injected turn in the bucket

$$f = \frac{h\omega}{2\pi} = \frac{h\beta c}{2\pi R}$$

$$\frac{\Delta f}{f} = \frac{\Delta \beta}{\beta} - \frac{\Delta R}{R} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right)\frac{\Delta p}{p}$$

H⁻ Injection/Accumulation





Injection into longitudinal phase space for Neutrino Factory booster synchrotron:

0.2 ms, ~150 turns, 180MeV

Injection symmetrical about B_{min}, so bucket is decelerating at the start, accelerating at the end.

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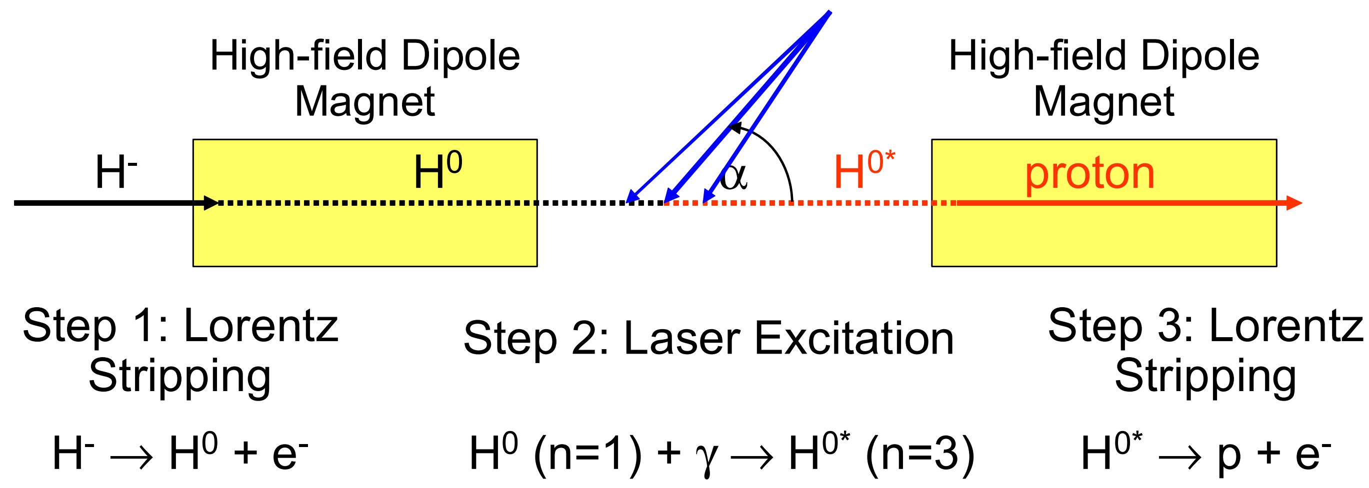
New ideas: Laser Stripping

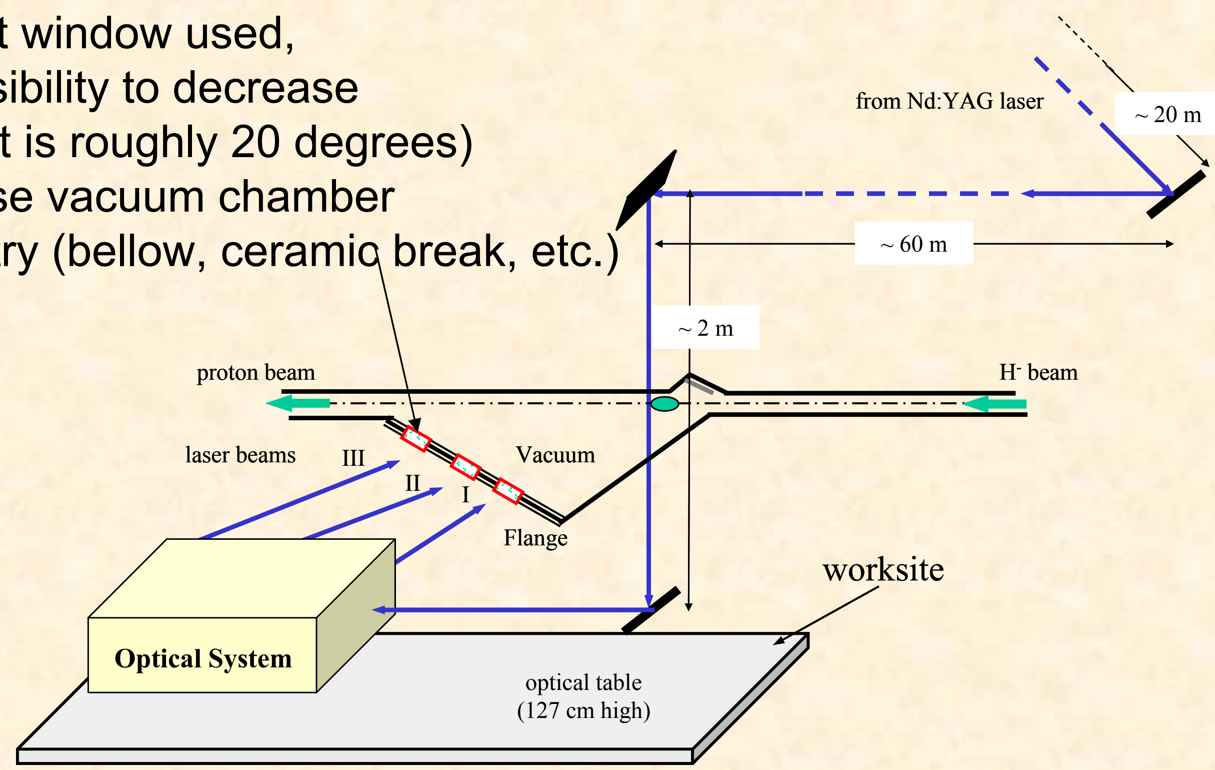


Three stage process

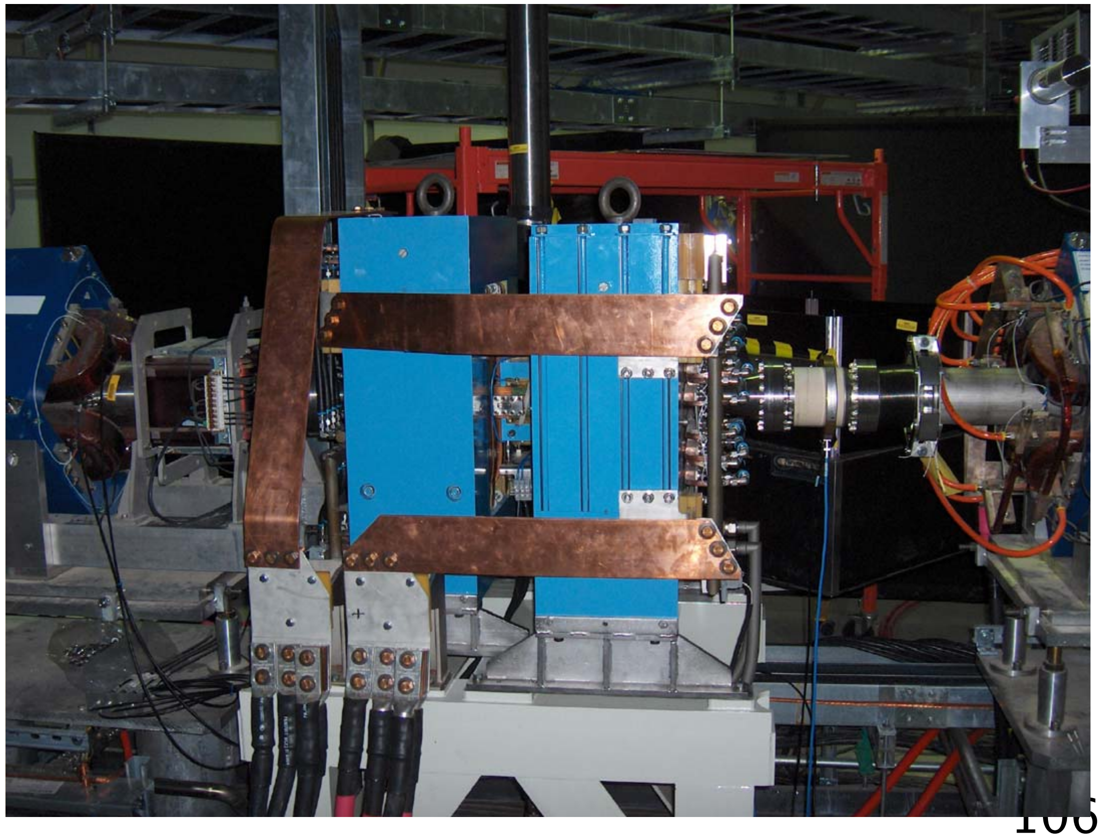
1. Remove loosely bound electron from H- with strong magnet(~2T)
2. Resonant excitation of n=1 to n=2 or n=3 transition with high-power laser
3. Remove excited electron with another strong magnet (~2T)

Minimal ion beam energy – 870 MeV. Laser system: 3rd harmonic Nd:Yag laser 7ns pulse

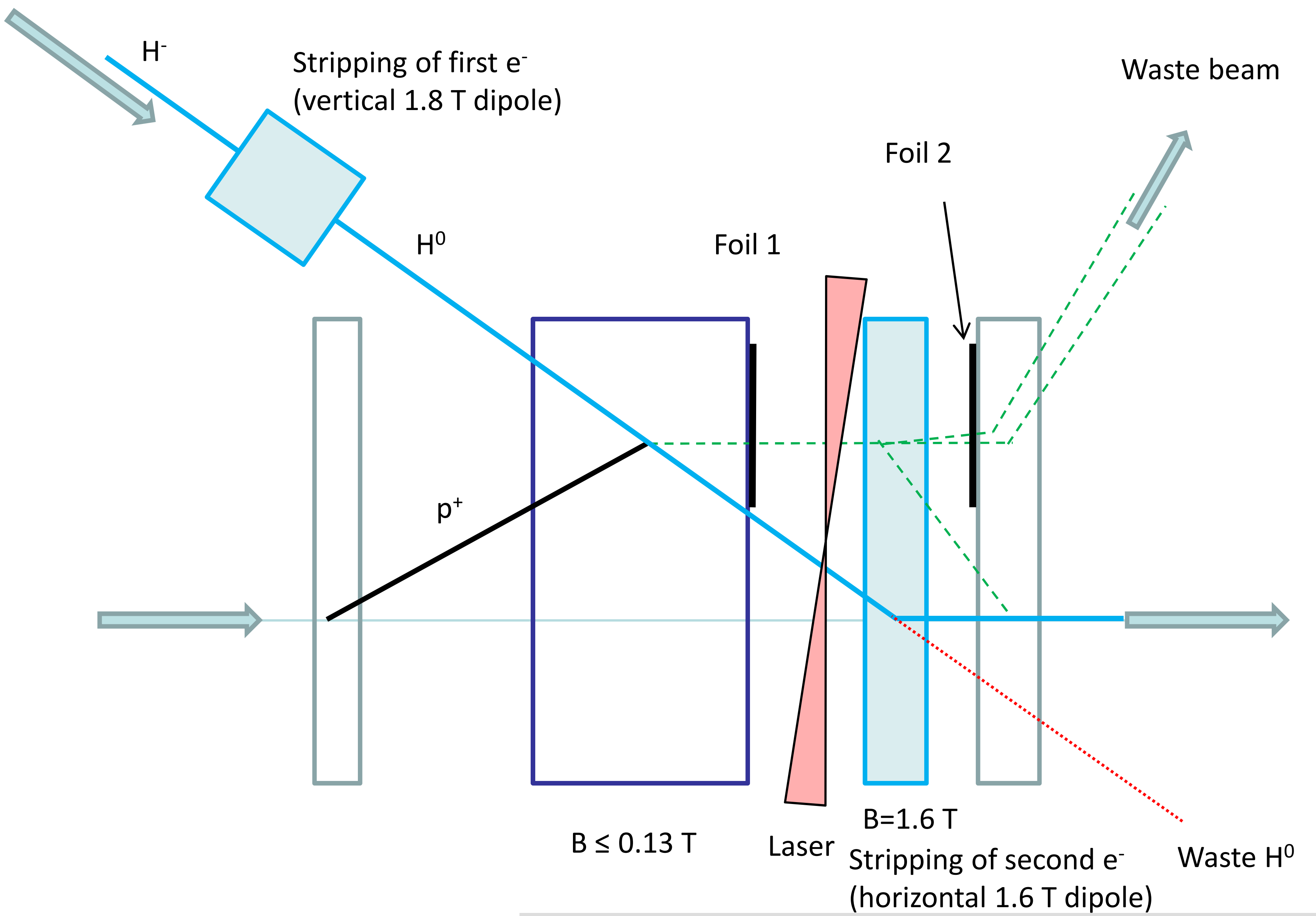
leftmost window used, no possibility to decrease angle (it is roughly 20 degrees) because vacuum chamber geometry (bellow, ceramic break, etc.)



Experiment at SNS



Possible Scheme 1



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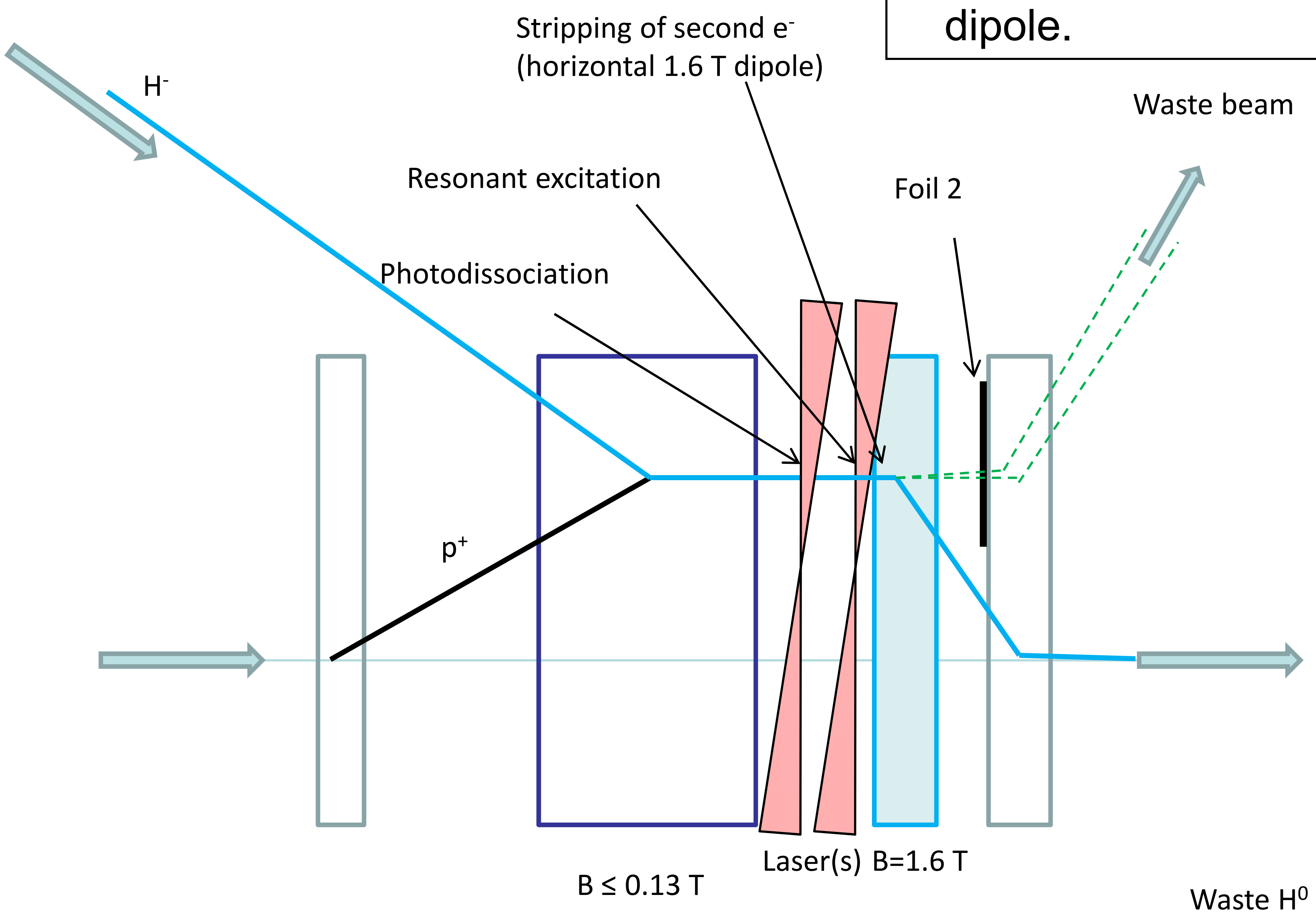
Possible Scheme 2

- First electron removed with laser photo-dissociation
- Resonant excitation of H0 to n=2 or n=3 level
- Lorentz strip remaining electron in injection chicane dipole.



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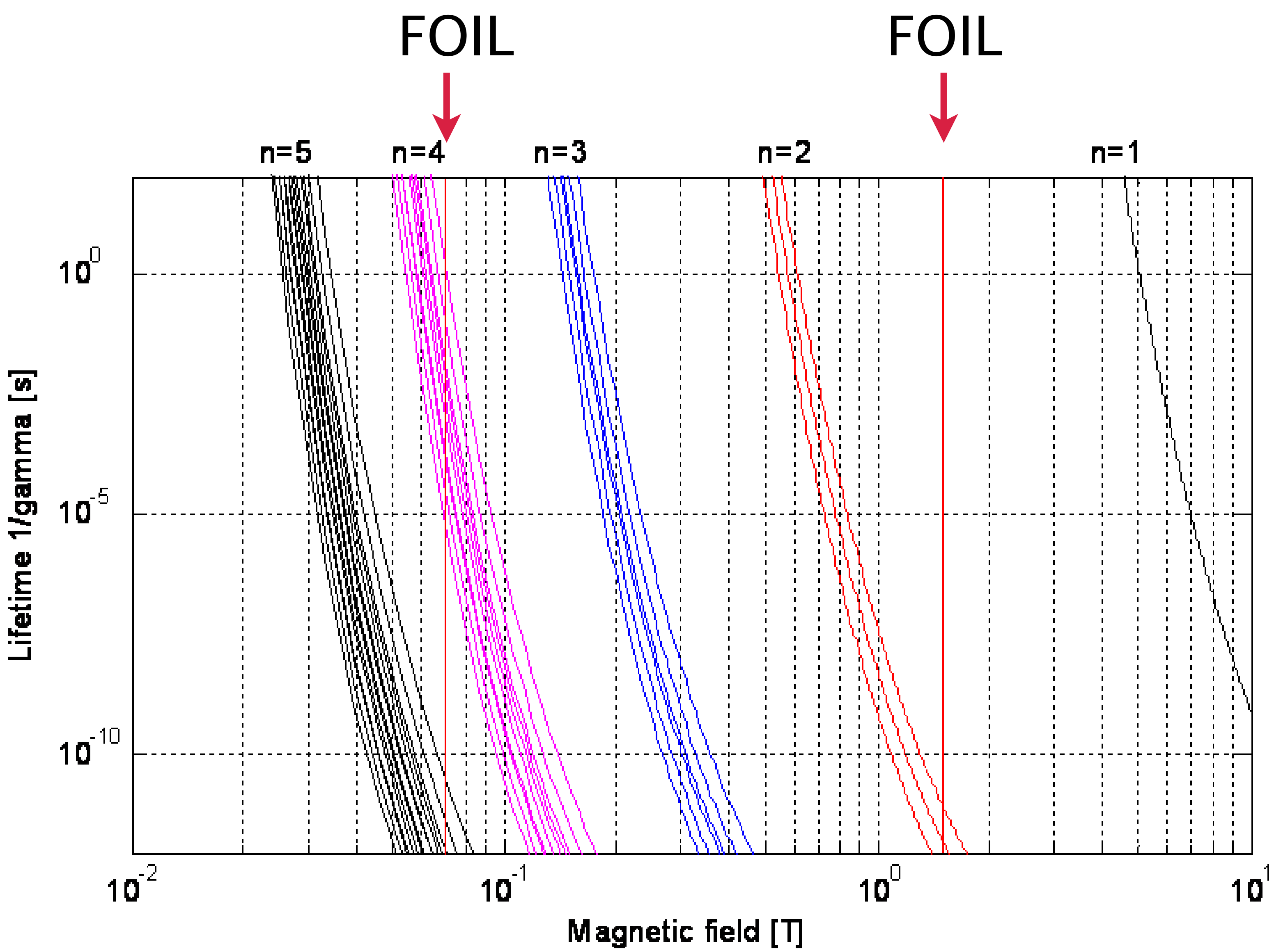
H^0 Excited States



Locate foils in fringe fields of magnets

- First foil at ~0.07 T so that n=4 states survive but states with n>5 are stripped immediately
- Place second foil such that n=2,3,4 are stripped to protons and join injected beam, while only n=1 survive as waste beam to dump

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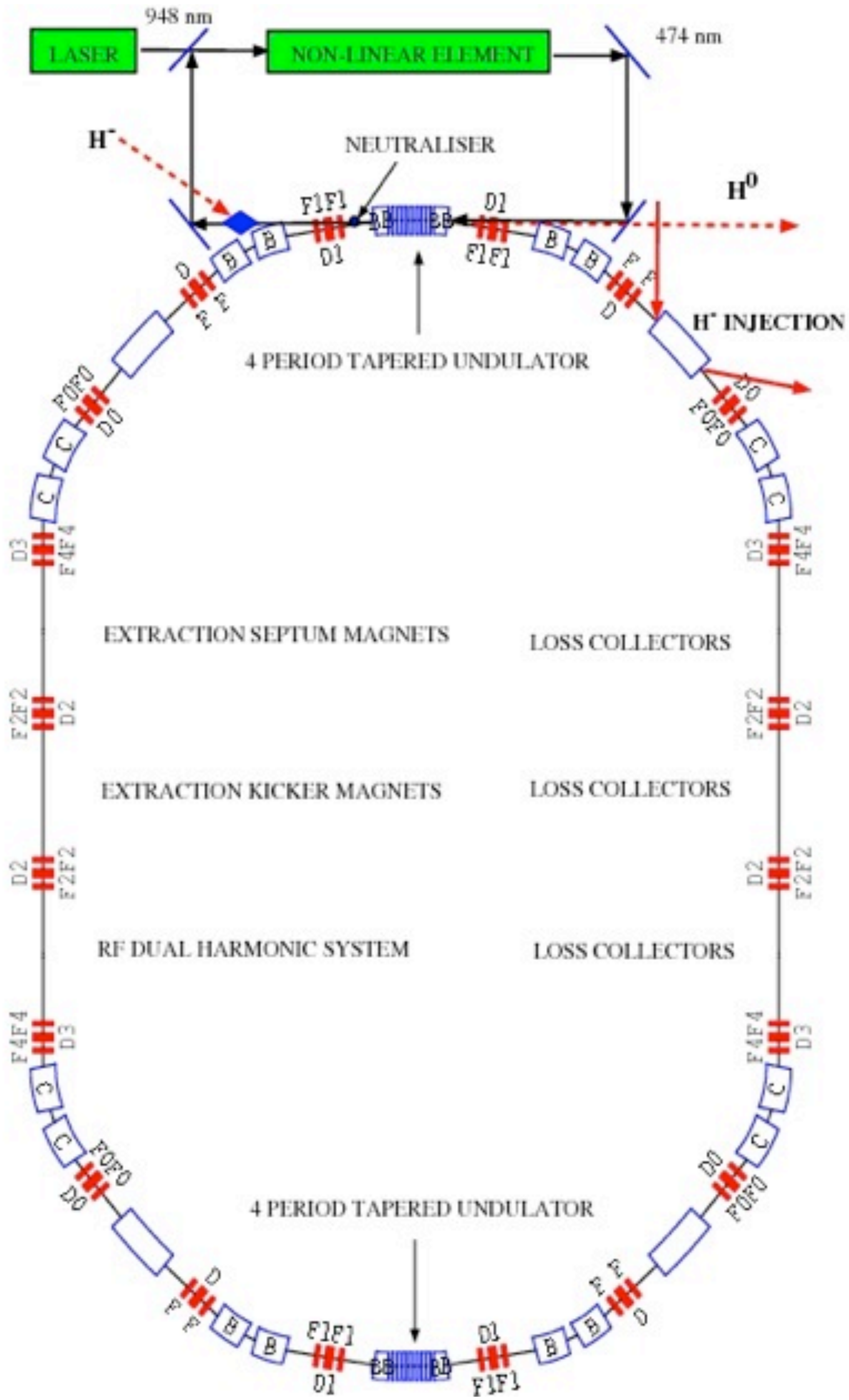
Laser Stripping for Short-Pulse ESS



- Ring lattice designed for laser stripping injection for ESS
- Also contains provision for conventional H- foil stripping
- H- converted to Ho in string electric field generated by relativistic interactions with magnetic field of an undulator.
- Laser and optical ring resonator excites n=3 quantum states.
- H0 states ionised in magnetic field of a long tapering undulator.
- Analysis of transition probabilities and rates of excitation suggest ionisation process needs to be repeated 8 times to achieve required % of H+. Undulator is then 5 m long, each period 1 m, field of 0.25 m half sine waves with 0.25 m free space between. Free space helps avoid broadening of the atomic absorption spectrum by Lorentx electric field during relativistic interation. Magnetic fields typically ~1 T.
- High efficiency but care needed to minimise dispersive effects within undulator.
- Problems in controlling emittance

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