3 GeV, 1.2 MW, RCS Booster and 10 GeV, 4.0 MW, NFFAG Proton Driver

G H Rees, ASTeC, RAL

Introduction

Studies for the ISS:

1. *Proton booster and driver rings for 50 Hz, 4 MW and 10 GeV.*
2. *Pairs of triangle and bow-tie, 20 (50 GeV) $\mu^{\pm}$ decay rings.*

Studies after the ISS:

1. *A 3 - 5.45 MeV electron model for the 10 GeV, proton NFFAG.*
2. *An alternative proton driver using a 50 Hz, 10 GeV, RCS ring.*
3. *A three pass, $\mu^{\pm}$ cooling, dog-bone re-circulator*

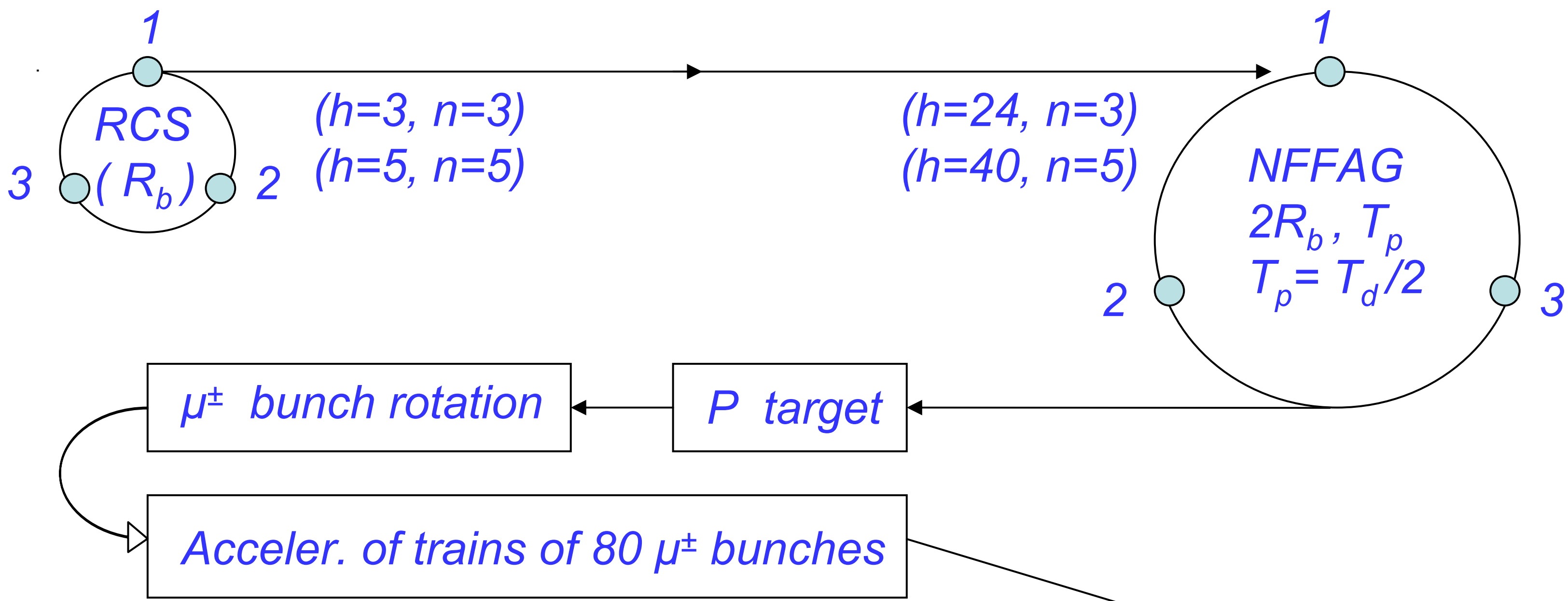
Proton Driver Parameter Changes for ISS

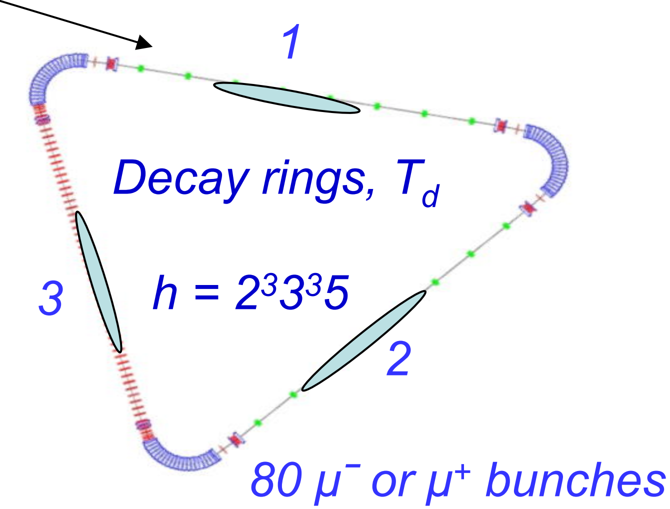
- *Pulse repetition frequency* *F = 15 to 50 Hz*
- *4 MW, proton driver energy* *T = (8 or 26) to 10 GeV*
- *No. of p bunches & $\mu^{\pm}$ trains* *n = 1 to (3 or 5)*

Reasons for the changes:

- *For adiabatic proton bunch compression to ~ 2 ns rms*
- *For lower peak & average beam currents in $\mu^{\pm}$ rings*
- *To allow partial beam loading compensation for the $\mu^{\pm}$*

Bunch Train Patterns

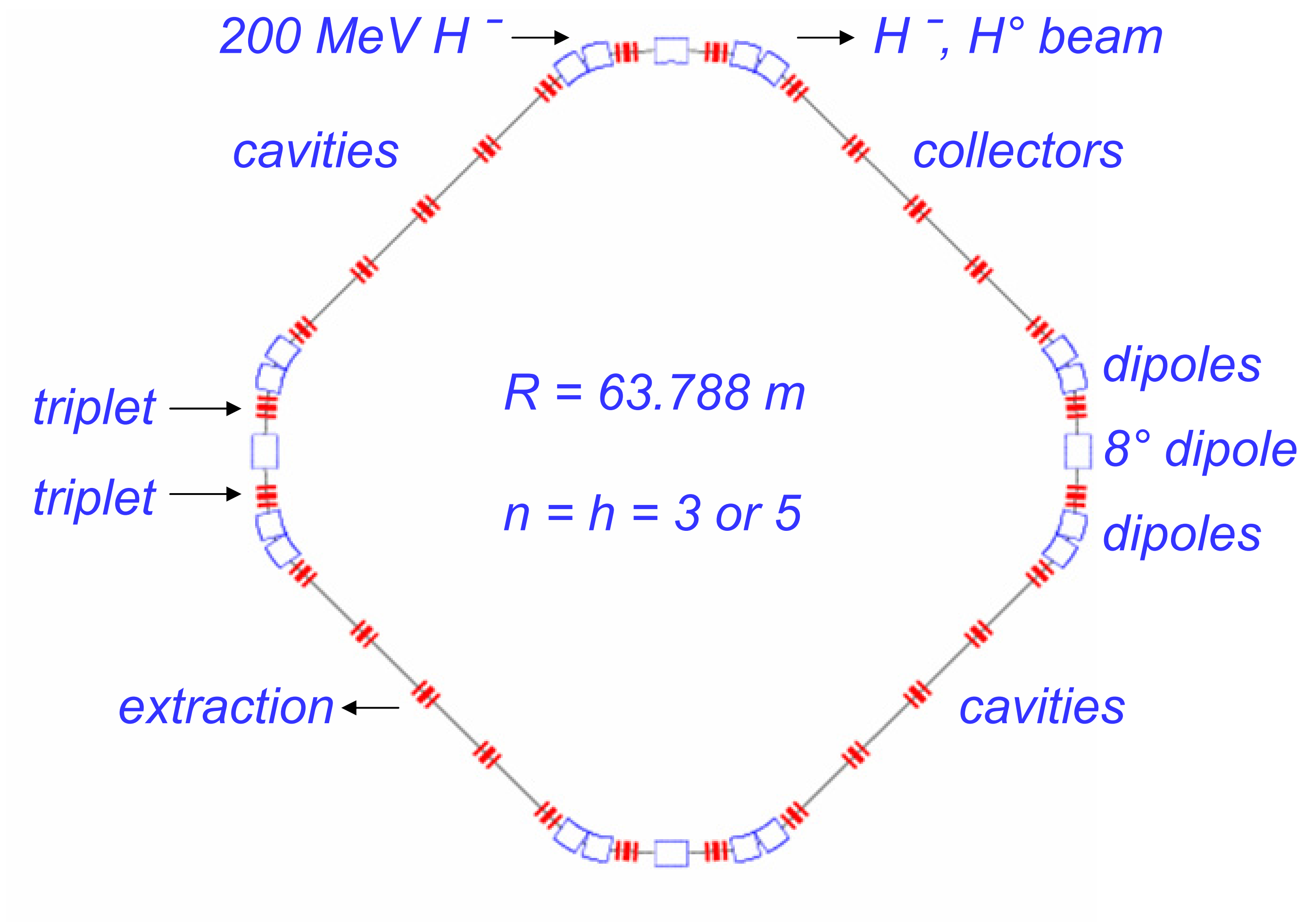




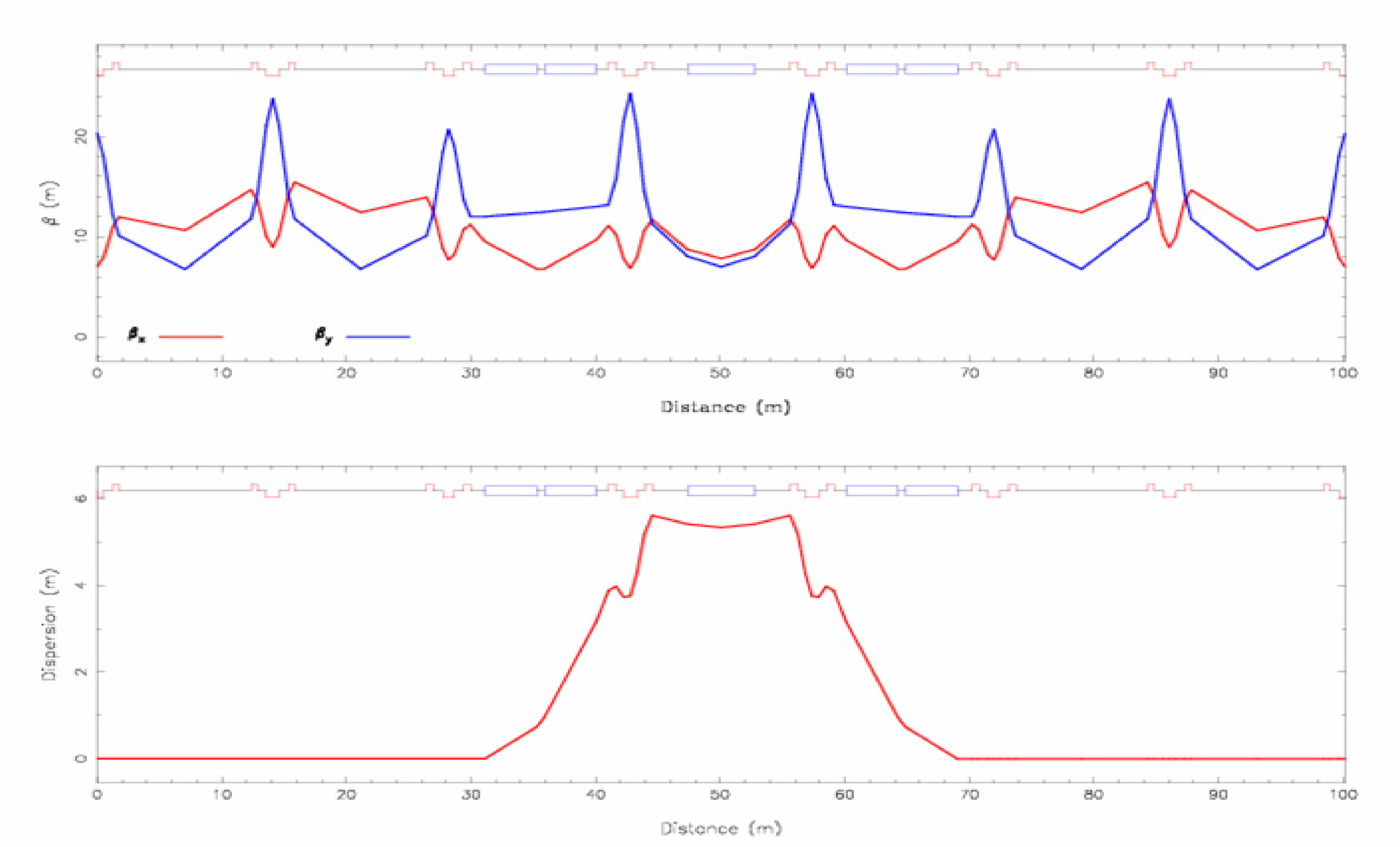
NFFAG ejection delays:
$(p + m/n)\ T_d$ for m = 1 to n (=3,5)

Pulse < 40 μs for liquid target
Pulse > 60 μs for solid target

Schematic Layout of 3 GeV, RCS Booster



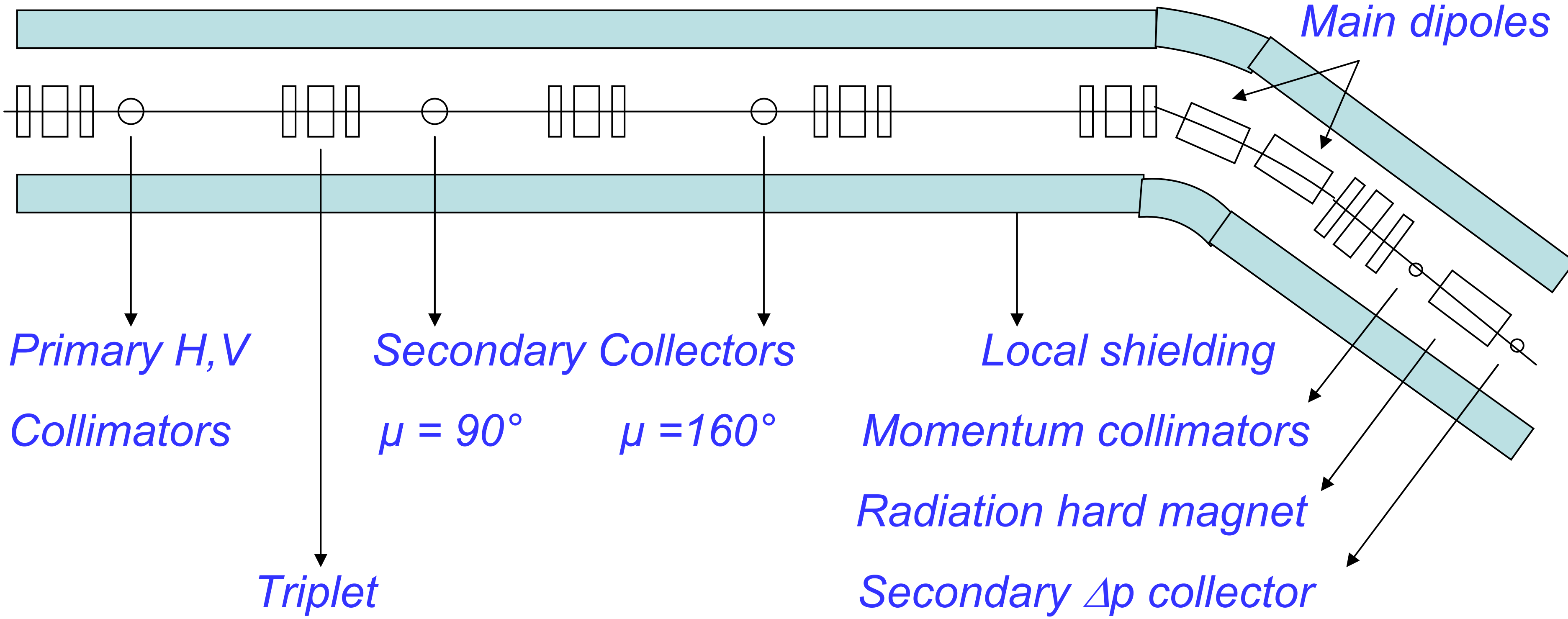
Booster Betatron and Dispersion Functions



Parameters for 50 Hz, 0.2 to 3 GeV Booster

Number of superperiods	4
Number of cells/superperiod	4(straights) + 3(bends)
Lengths of the cells	4(14.0995) + 3(14.6) m
Free length of long straights	16 x 10.6 m
Mean ring radius	63.788 m
Betatron tunes (Q_v, Q_h)	6.38, 6.30
Transition gamma	6.57
Main dipole fields	0.185 to 1.0996 T
Secondary dipole fields	0.0551 to 0.327 T
Triplet length/quad gradient	3.5 m/1.0 to 5.9 T m^{-1}

Beam Loss Collection System



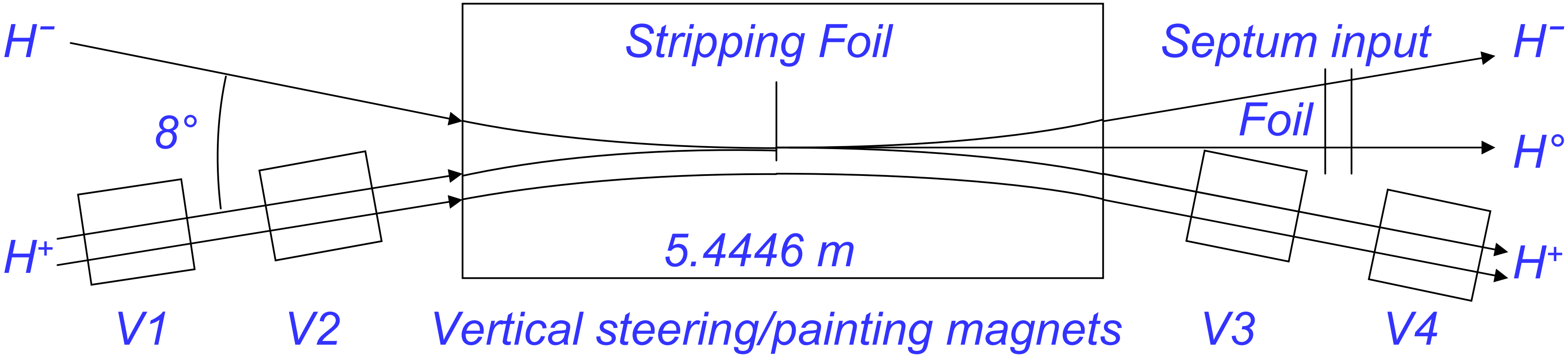
Choice of Lattice

- *ESS-type, 3-bend achromat, triplet lattice chosen*
- *Lattice is designed around the H^- injection system*
- *Dispersion at foil to simplify the injection painting*
- *Avoids need of injection septum unit and chicane*
- *Separated injection; all units between two triplets*
- *Four superperiods, with >100 m for RF systems*
- *Locations for momentum and betatron collimation*
- *Common gradient for all the triplet quadrupoles*
- *Five quad lengths but same lamination stamping*
- *Bending with 20.5° main & 8° secondary dipoles*

Schematic Plan of H^- Injection

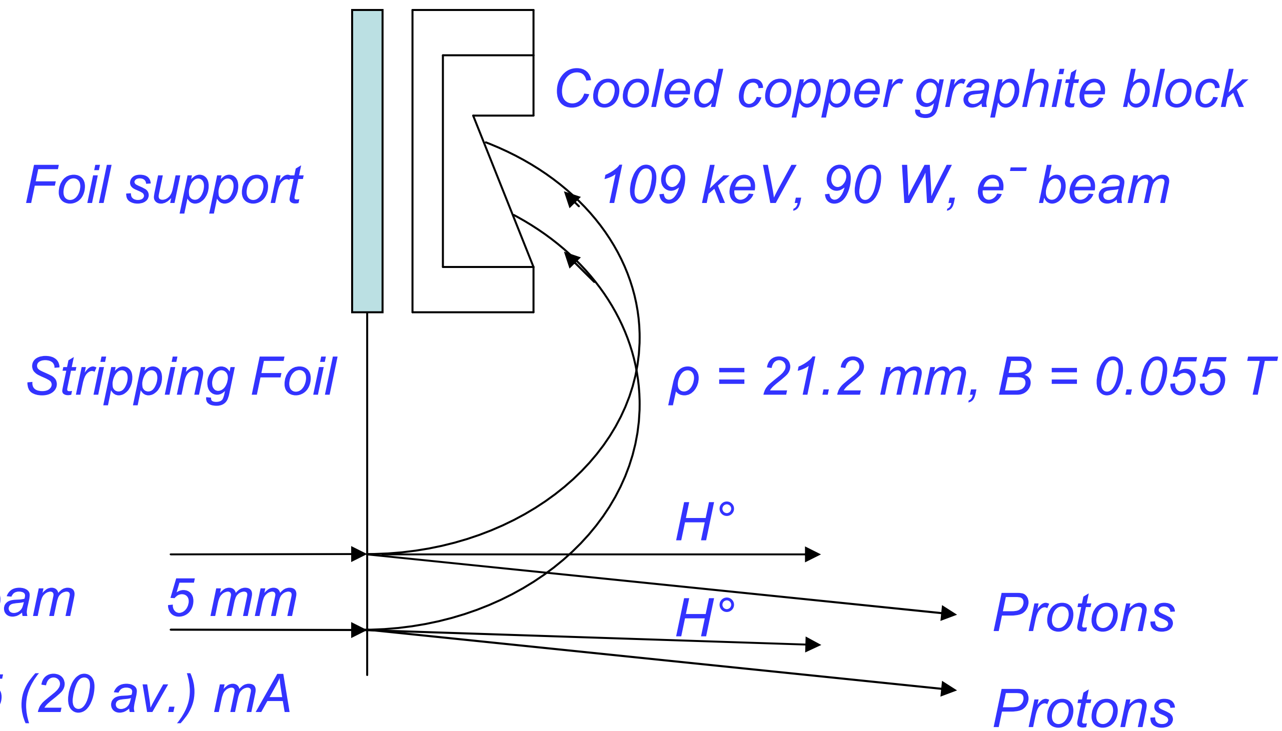
Optimum field for n = 4 & 5, H° Stark state lifetimes.

0.0551 T, Injection Dipole



- Horizontal painting via field changes, momentum ramping & rf steering
- Separated system with all injection components between two triplets.
- H^- injection spot at foil is centred on an off-momentum closed orbit.

Electron Collection after H^- Stripping



200 MeV, 80 kW, H^- beam

170 injected turns, 28.5 (20 av.) mA

Foil lattice parameters : $\beta_v = 7.0$ m, $\beta_h = 7.8$ m, $D_h = 5.3$ m, $D_h/\sqrt{\beta_h} = 1.93\ m^{1/2}$

H^- parameters at stripping foil ; $\beta_v = 2.0$ m, $\beta_h = 2.0$ m, $D_h = 0.0$ m, $D_h' = 0.0$

Anti-correlated, H^- Injection Painting

Vertical acceptance

H^- injected beam

Initial closed orbits

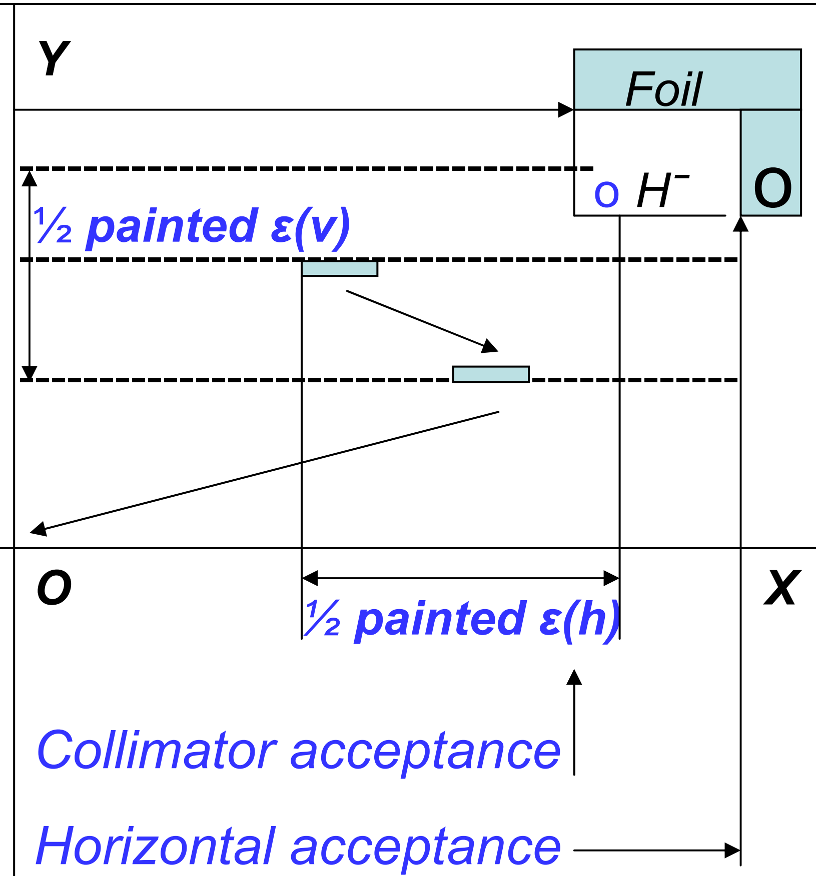
Final closed orbits

Collapsed closed orbits

Δp/p spread in X closed orbits

Small v, big h amplitudes at start

Small h, big v amplitudes at end.



For correlated transverse painting : interchange X closed orbits

Why Anti-correlated Painting?

Assume an elliptical beam distribution of cross-section (a, b).

The transverse space charge tune depressions/spreads are :

$$\delta Q_v = 1.5\,[1 - S/\int(\beta_v\, ds / b(a+b))]\,\delta Q_v\,(uniform)$$

$$4S = \int[\beta_v/b(a+b)^2]\,[(y^2\,(a + 2b)/\,2b^2\,) + (\,x^2/\,a)]\,ds$$

Protons with (x = 0, y = 0) have $\delta Q_v = 1.5\ \delta Q_v$ (uniform distrib.)

Protons with (x = 0, y = b) have $\delta Q_v \sim 1.3\ \delta Q_v$ (uniform distrib.)

Protons with (x = a, y = 0) or (x = a/2, y= b/2) have ~ 1.3 factor.

δQ shift is thus less for anti-correlated than correlated painting.

The distribution may change under the effect of space charge.

Emittances and Space Charge Tune Shifts

Design for a Laslett tune shift (uniform distribution) of $\delta Q_v = 0.2$.
An anti-correlated, elliptical, beam distribution has a $\delta Q_v = 0.26$.

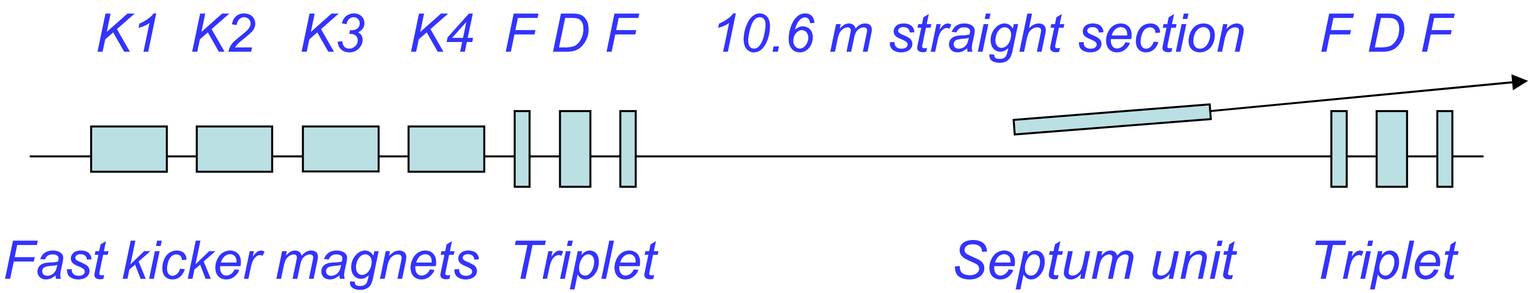
For $5\ 10^{13}$ protons at 200 MeV, with a bunching factor of 0.47, the estimated, normalised, rms beam emittances required are:

$$\varepsilon_{\sigma\, n} = 24\ (\pi)\ \text{mm mrad}$$
$$\varepsilon_{max} = 175\ (\pi)\ \text{mm mrad}$$

The maximum, vertical beam amplitudes (D quads) are 66 mm.
Maximum, horizontal beam amplitudes (in F quads) are 52 mm.

Maximum, X motions at high dispersion regions are < 80 mm.
Max. ring/collimator acceptances are 400/200 (π) mm mrad.

Fast Extraction at 3 GeV

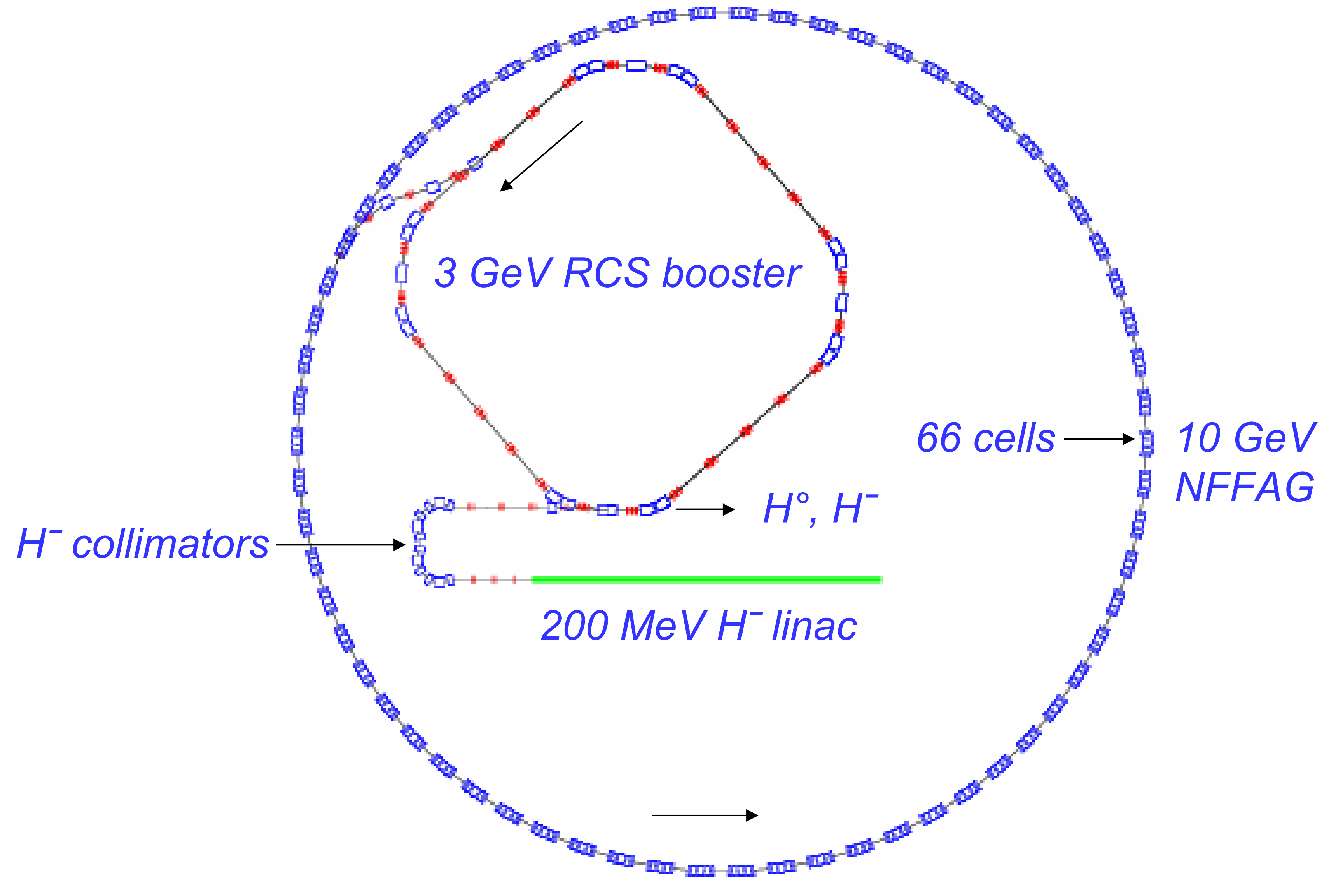


- *Horizontal deflections for the kicker and septum magnets*
- *Rise / fall times for 5 (3) pulse, kicker magnets = 260 ns*
- *Required are 4 push-pull kickers with 8 pulser systems*
- *Low transverse impedance for (10 Ω) delay line kickers*
- *Extraction delays, ΔT, from the booster and NFFAG rings*
- *R & D necessary for the RCS and the Driver pulsers*

RF Parameters for 3 GeV Booster

• Number of protons per cycle	$5\ 10^{13}$ (1.2 MW)
• RF cavity straight sections	106 m
• Frequency range for h = n = 5	2.117 to 3.632 MHz
• Bunch area for h = n = 5	0.66 eV sec
• Voltage at 3 GeV for $\eta_{sc} < 0.4$	417 kV
• Voltage at 5 ms for $\varphi_s = 48°$	900 kV
• Frequency range for h = n = 3	1.270 to 2.179 MHz
• Bunch area for h = n = 3	1.1 eV sec
• Voltage at 3 GeV for $\eta_{sc} < 0.4$	247 kV
• Voltage at 5 ms for $\varphi_s = 52°$	848 kV

Schematic Layout of Booster and Driver



Homing Routines in Non-linear, NFFAG Program

- *A linear lattice code is modified for estimates to be made of the non-linear fields in a group of FFAG magnets.*
- *Bending radii are found from average field gradients between adjacent orbits & derived dispersion values, D.*
- *D is a weighted, averaged, normalized dispersion of a new orbit relative to an old, and the latter to the former.*
- *A first, homing routine obtains specified betatron tunes. A second routine is for exact closure of reference orbits*
- *A final, limited-range, orbit-closure routine homes for γ-t. Accurate estimates are made for reference orbit lengths.*
- *Full analysis needs processing the lattice output data & ray tracing in 6-D simulation programs such as Zgoubi.*

Non-linear Fields and Reference Orbits

- *Low ampl. Twiss parameters are set for a max. energy cell.*
- *Successive, adjacent, lower energy reference orbits are then found, assuming linear, local changes of the field gradients.*
- *Estimates are repeated, varying the field gradients for the required tunes, until self-consistent values are obtained for:*

the bending angle for each magnet of the cell
the magnet bending radii throughout the cell
the beam entry & exit angle for each magnet
the orbit lengths for all the cell elements, and
the local values of the magnet field gradients

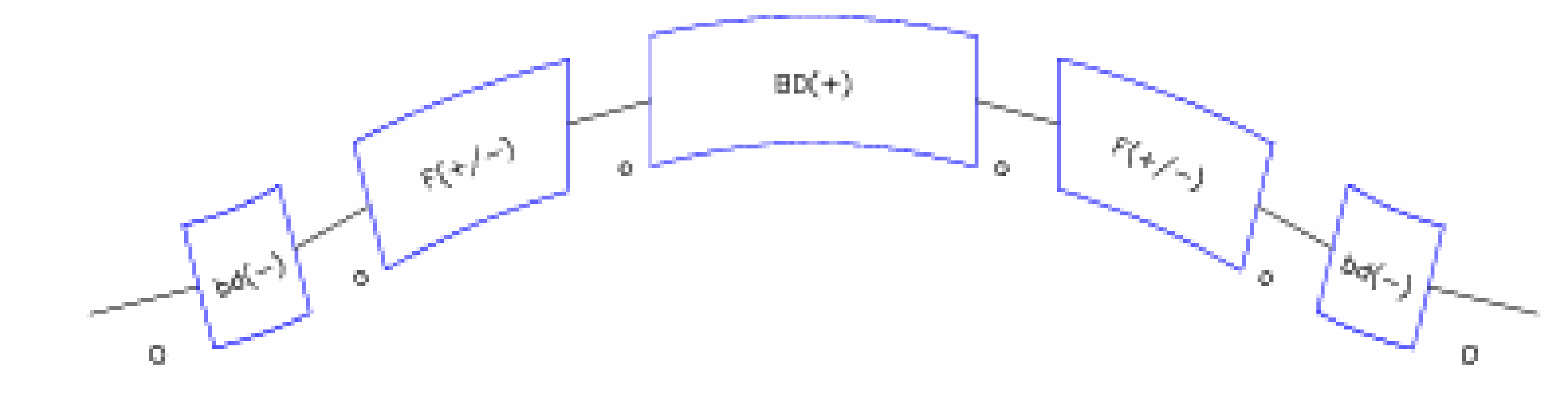
The Non-linear, Non-scaling NFFAG

- Cells have the arrangement: O-bd-BF-BD-BF-bd-O
- The bending directions are : - + + + -
- Number of magnet types is: 3
- Number of cells in lattice is: 66

- The length of each cell is: 12.14 m
- The tunes, Q_h and Q_v ,are: 20.308 and 15.231
- Non-isochronous FFAG: $\xi_v \approx 0$ and $\xi_h \approx 0$
- Gamma-t is imaginary at 3 GeV, and ≈ 21 at 10 GeV

- Full analysis needs processing non-linear lattice data & ray tracing in 6-D simulation programs such as Zgoubi

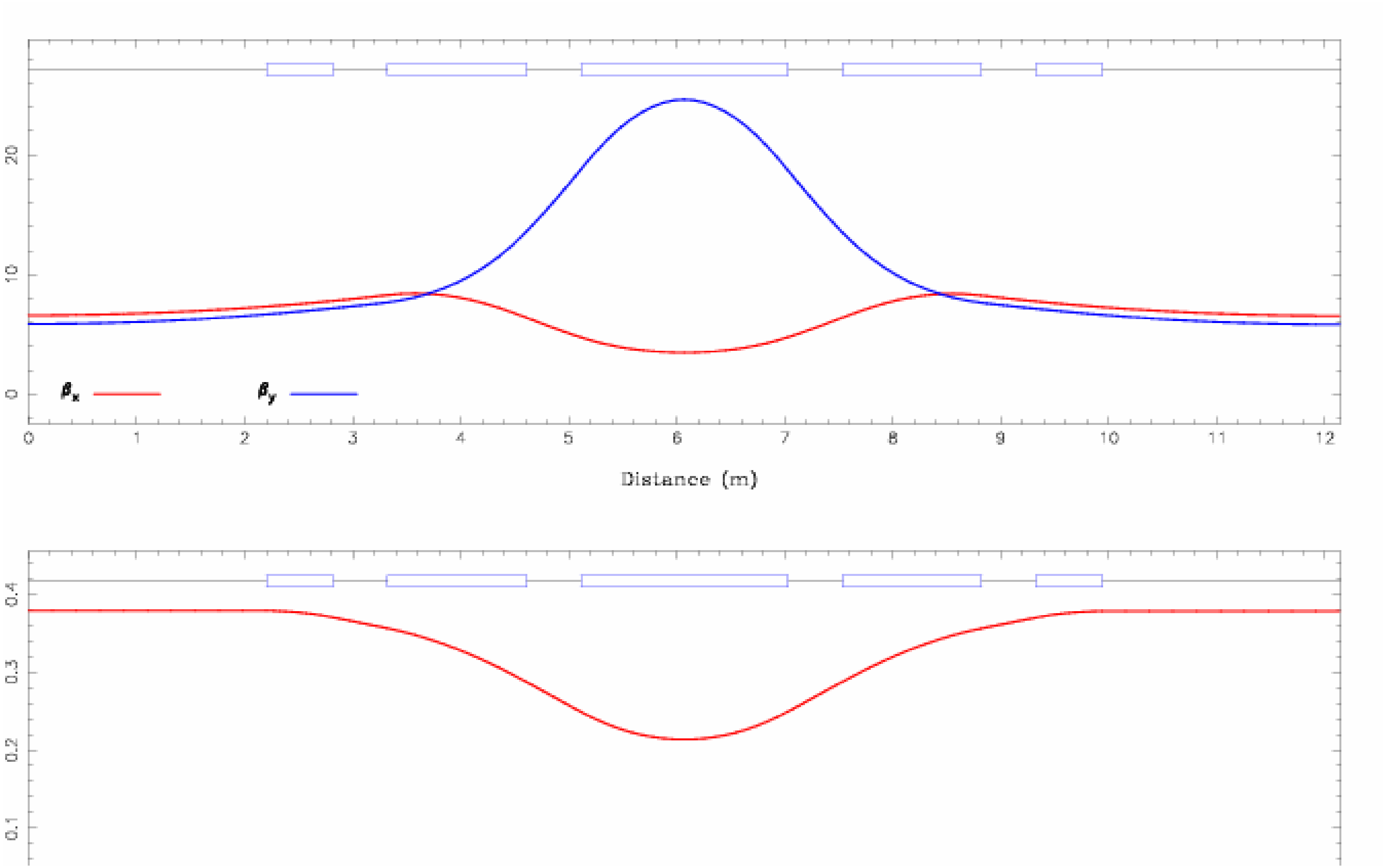
Lattice Cell for the NFFAG Ring



	bd(-)	BF(+)	BD(+)	BF(+)	bd(-)	
2.2	0.62	1.29	1.92 (m)	1.29	0.62	2.2
	–1.65°	3.5523°	1.65°	3.5523°	–1.65°	

Lengths and angles for the 10.0 GeV closed orbit

10 GeV Betatron & Dispersion Functions



Gamma-t vs. γ for the Driver and E-model

Proton Driver		Electron Model	
γ =E/Eo	gamma-t	γ =E/Eo	gamma-t
11.658	21.8563	11.658	19.9545
10.805	23.1154	10.980	22.4864
10.379	23.9225	10.393	24.2936
9.953	24.8996	9.806	28.9955
9.100	27.6544	9.219	51.1918
8.673	29.7066	8.632	34.7566 i
8.247	32.5945	8.045	19.6996 i
7.608	40.0939	7.458	14.2350 i
6.968	64.0158	6.871	11.8527 i
4.197	18.9302 i (imag.)	–	–

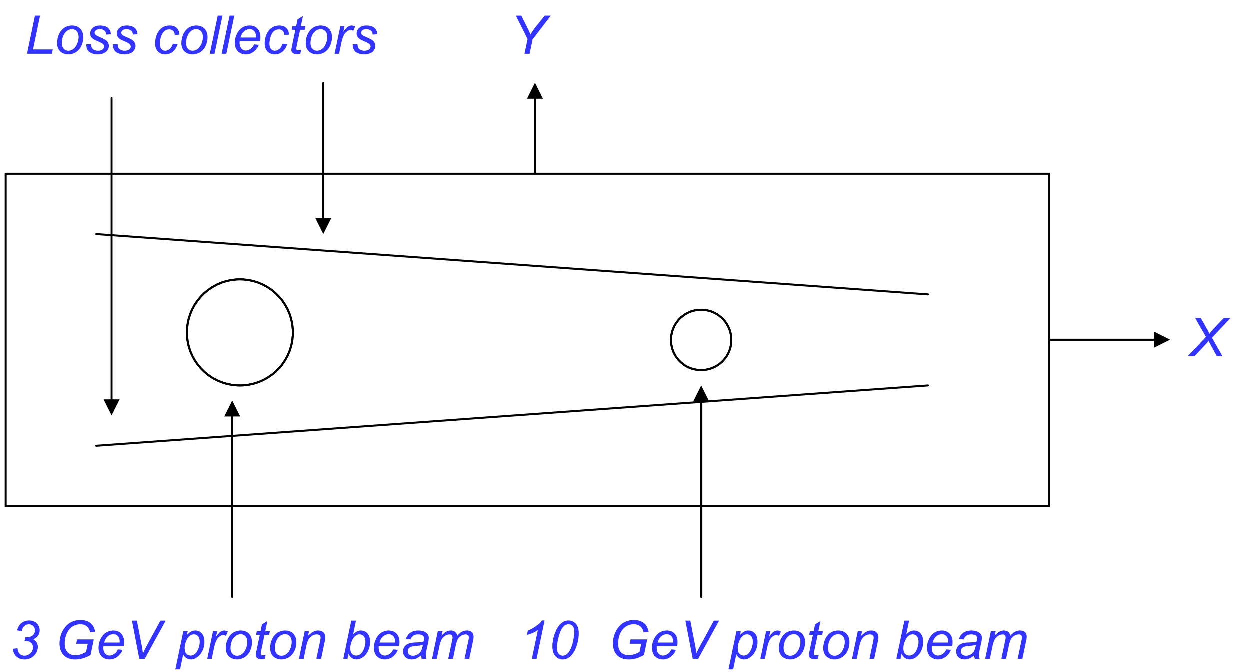
Loss Levels for NFFAG Proton Driver

- *Beam power for the 50 Hz Proton Driver = 4 MW*

- *Total loss through the extraction region < 1 part in10^4*
- *Average loss outside coll./ extr. region < 1 part in10^4*
- *Total loss in primary & sec. collimators = 1 part in10^3*

- *Remotely operated positions for primary collimators.*
- *Quick release water fittings and component flanges.*
- *Local shielding for collimators to reduce air activation.*

Vertical Collimation in the NFFAG



Coupling may limit horizontal beam growth

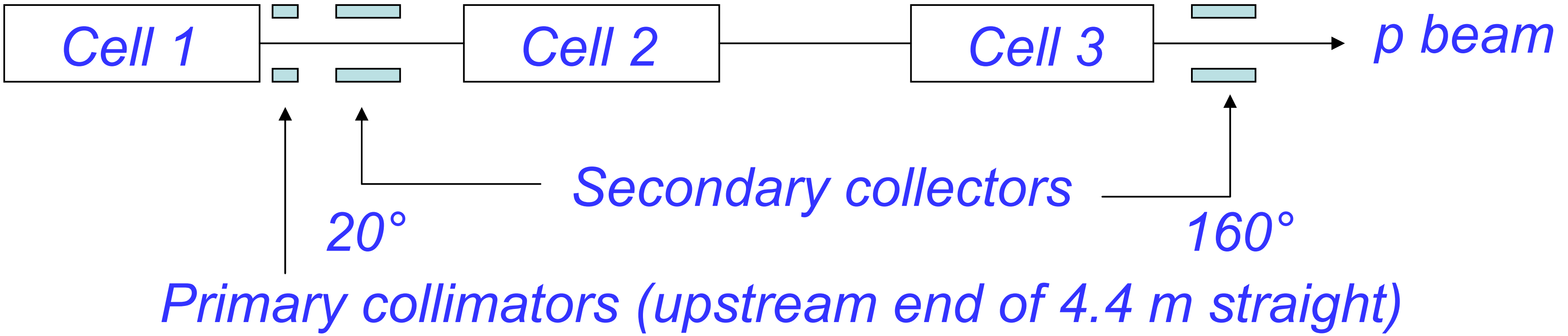
Loss Collection for the NFFAG

- *Vertical loss collection is easier than in an RCS*
- *ΔP loss collection requires beam in gap kickers*

- *Horizontal beam collimation prior to the injection*
- *Horizontal loss collection only before the ejection*

- *Minimize the halo growth during the acceleration*
- *Minimise non-linear excitations as shown later.*

NFFAG Loss Collection Region



- Direct beam loss localised in the collection region
- Beam 2.5 σ, Collimator 2.7 σ and Acceptance 4 σ

NFFAG Non-linear Excitations

Cells	Q_h	Q_v	3rd Order	Higher Order
4	0.25	0.25	zero	$nQ_h=nQ_v$ & 4th order
5	0.20	0.20	zero	$nQ_h=nQ_v$ & 5th order
6	0.166	0.166	zero	$nQ_h=nQ_v$ & 6th order
9	0.222	0.222	zero	$nQ_h=nQ_v$ & 9th order
13	4/13	3/13	zero to	13th except $3Q_h=4Q_v$

Use (13 x 5) + 1 = 66 such cells for the NFFAG

Variation of the betatron tunes with amplitude?

γ-t imaginary at low energy and ~ 20 at 10 GeV

Bunch Compression at 10 GeV

For 5 proton bunches:
Longitudinal areas of bunches = 0.66 eV sec
Frequency range for a h of 40 = 14.53-14.91 MHz
Bunch extent for 1.18 MV/ turn = 2.1 ns rms
Adding of h = 200, 3.77 MV/turn = 1.1 ns rms

For 3 proton bunches:
Longitudinal areas of bunches = 1.10 eV sec
Frequency range for a h of 24 = 8.718-8.944 MHz
Bunch extent for 0.89 MV/ turn = 3.3 ns rms
Adding of h = 120, 2.26 MV/turn = 1.9 ns rms

Booster and Driver tracking studies are needed

50 Hz,10 GeV, RCS Alternative

- *Same circumference as for the outer orbit of the NFFAG*
- *Same box-car stacking scheme for the $\mu^{\pm}$ decay rings*
- *Same number of proton bunches per cycle (3 or 5)*
- *Same rf voltage for bunch compression (same gamma-t)*
- *Increased rf voltage for the proton acceleration (50% ?)*
- *3 superperiods of (15 arc cells and 6 straight sections)*
- *5 groups of 3 cells in the arcs for good sextupole placings*
- *2 quadrupole types of different lengths but same gradient*
- *2 dipole magnet types, both with a peak field of 1.0574 T*

10 GeV NFFAG versus RCS

Pros:

- *Allows acceleration over more of the 50 Hz cycle*
- *No need for a biased ac magnet power supply*
- *No need for an ac design for the ring magnets*
- *No need for a ceramic chamber with rf shields*
- *Gives more flexibility for the holding of bunches*

Cons:

- *Requires a larger (~ 0.33 m) radial aperture*
- *Needs an electron model to confirm viability*

R & D Requirements

Development of an FFAG space charge tracking code.
Tracking with space charge of booster and driver rings.

Building an electron model for NFFAG proton driver.
Magnet design & costing for RCS, NFFAG & e-model.
.
Development of multiple pulse, fast kicker systems.
Site lay-out drawings & conventional facilities design

NFFAG study (with beam loading) for $\mu^{\pm}$ acceleration