NFFAG & IFFAG Loss Collectors

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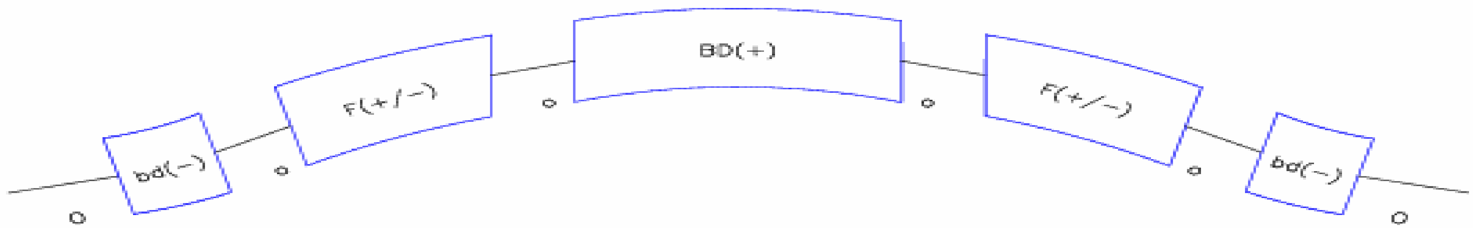
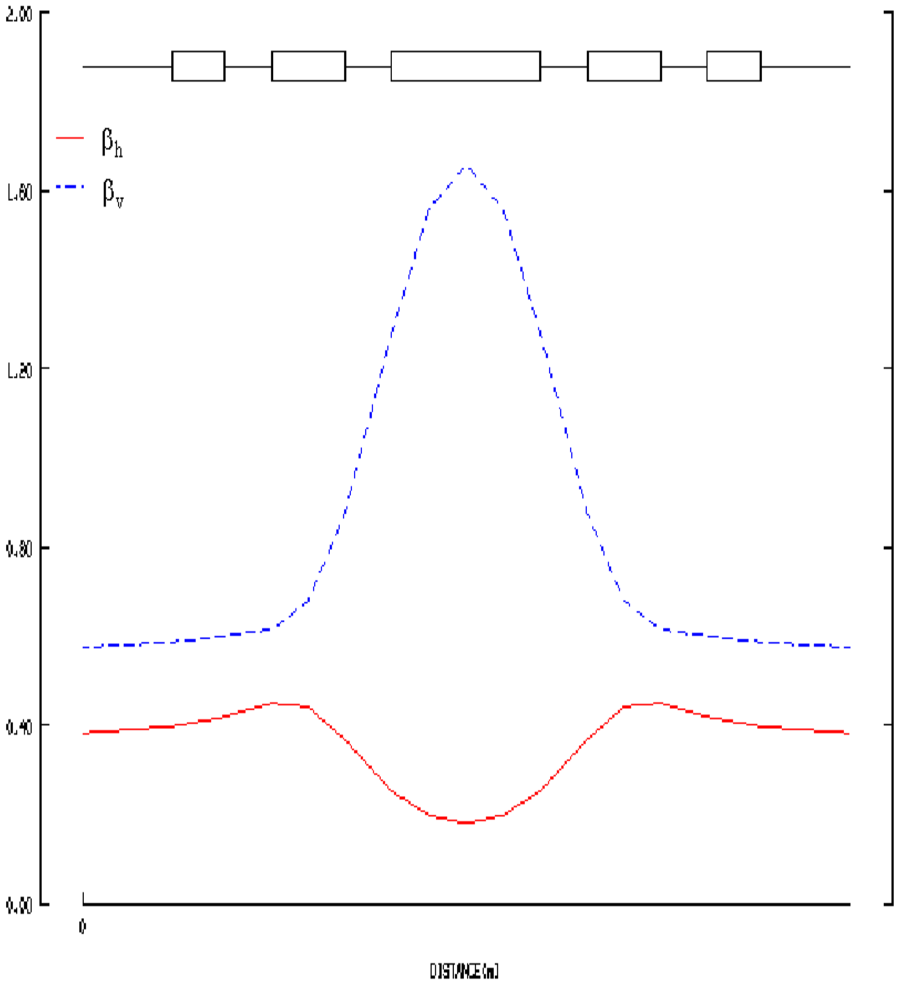
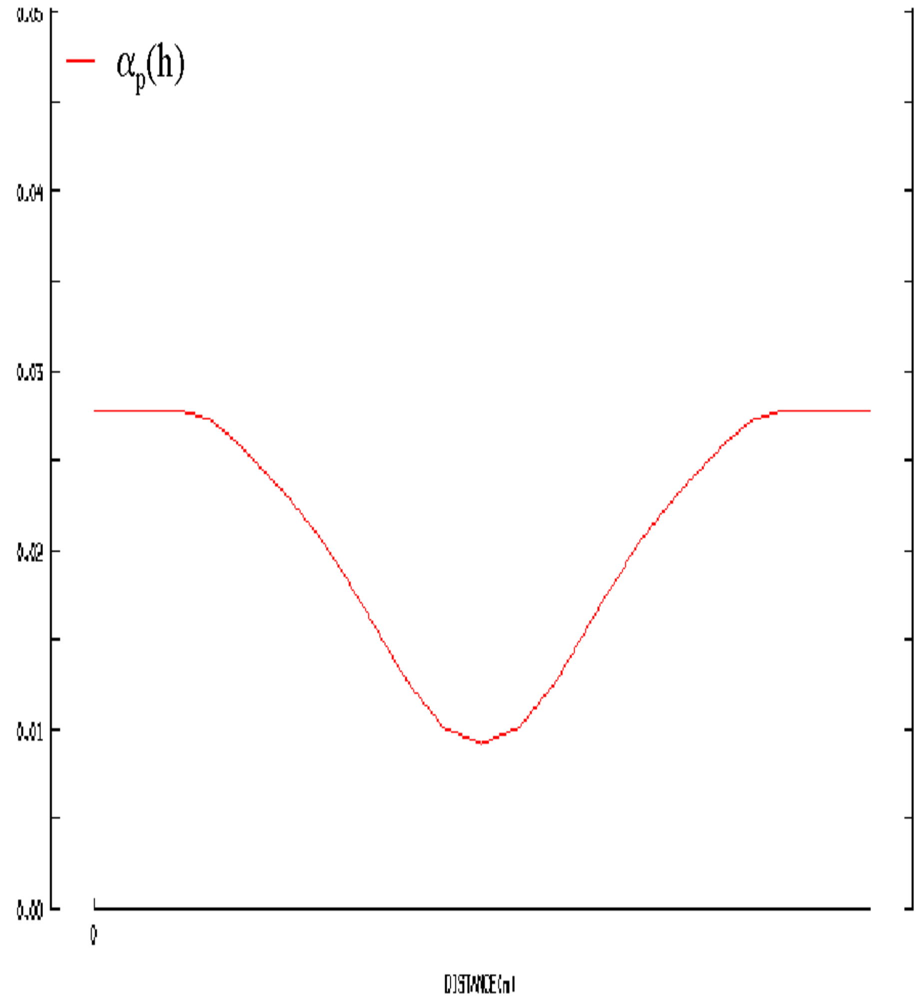
NFFAG and IFFAG Lattice Cells



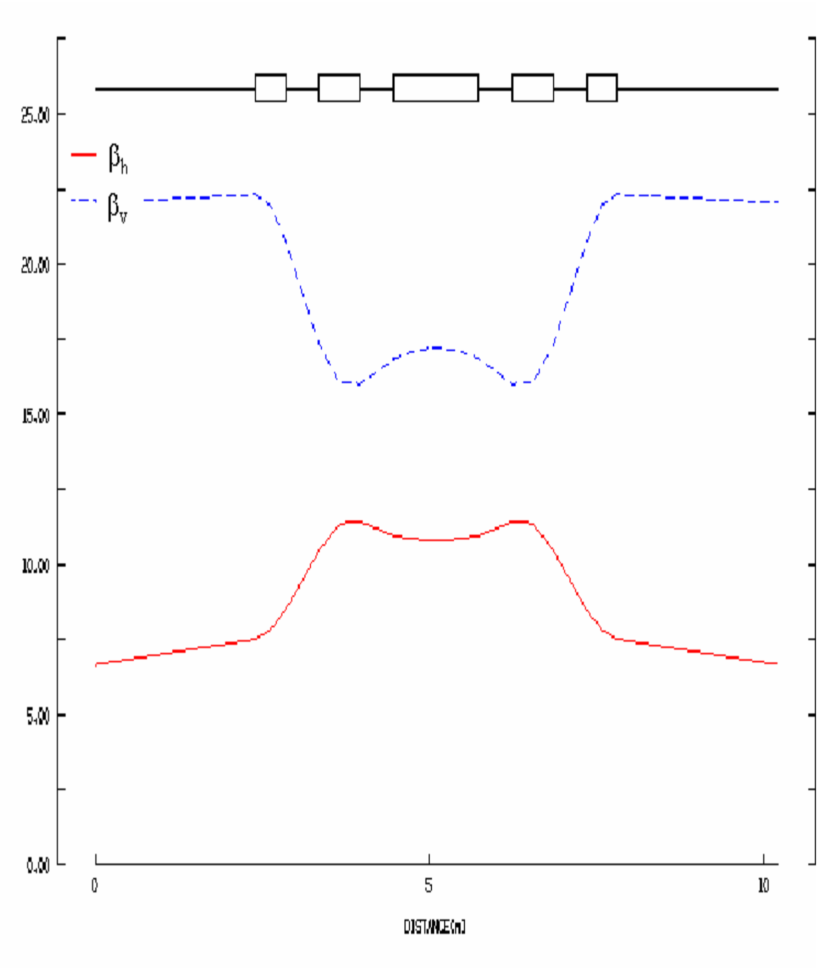
- Cells have the arrangement: O-bd-BF-BD-BF-bd-O.
- NFFAG: non-isochronous ; $\xi_v = 0$, $\xi_h = 0$.
- IFFAG: isochronous ($\gamma_t = \gamma$) ; $\xi_v = 0$, $\xi_h = +ve$.
- NFFAGI and IFFAGI have normal & insertion cells.
- Different length straights in normal & insertion cells.
- There is closed orbit matching between single cells.

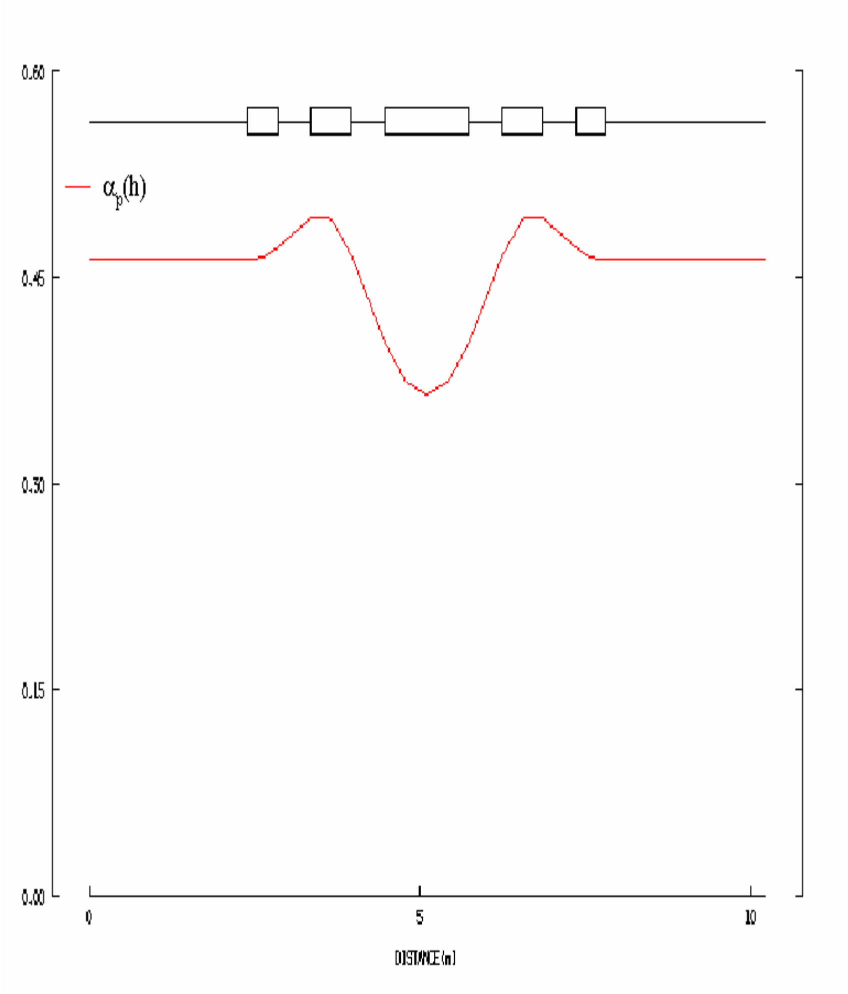
Typical Lattice Functions at Max Energy





Typical Lattice Functions at Min Energy





Homing Routines in a Modified Lattice Program

- *A lattice code is modified to allow estimates to be made for 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 amplitude, Twiss params. 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 γ-t , 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*

Beam Loss Collectors

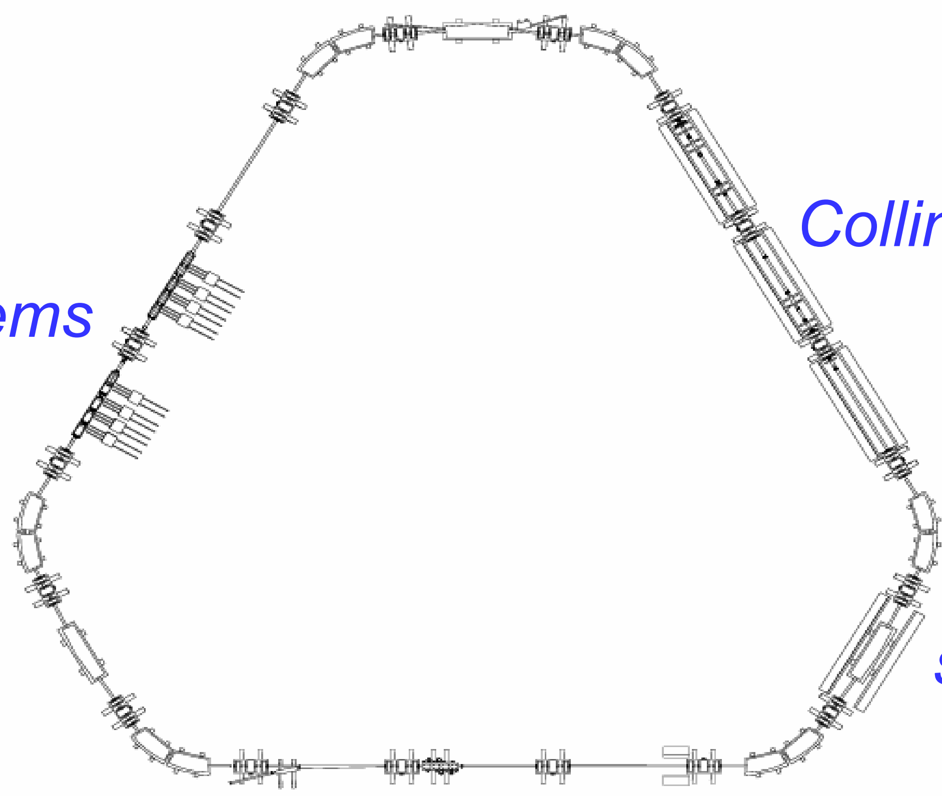
RCS: Betatron collimation in a zero dispersion region.
Momentum collimation at high norm. dispersion.

NFFAG: V betatron collection in low dispersion areas.
Momentum growth limited by beam in gap kicker.

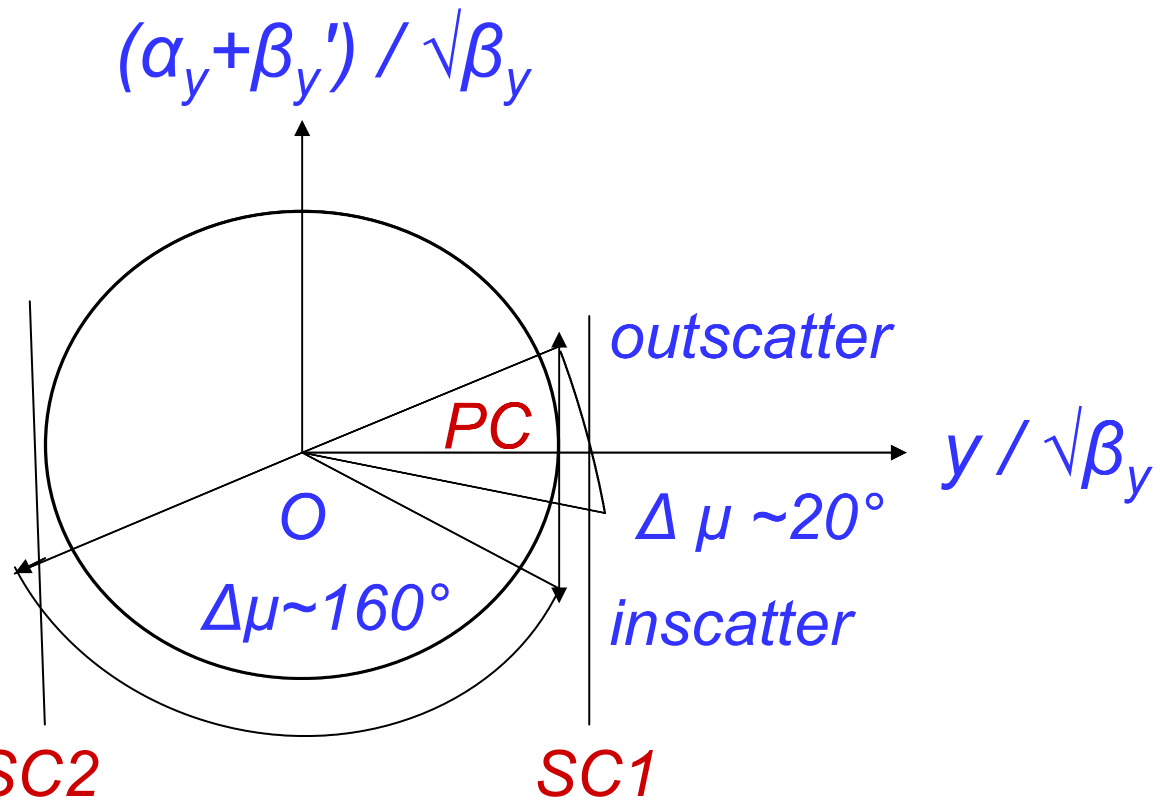
IFFAG: V betatron collection in low dispersion areas.
Remove non-extracted beam between cycles.

The betatron collection requires constant tune values.
FFAG h-betatron collection at injection & ejection only.

Collimator Shielding

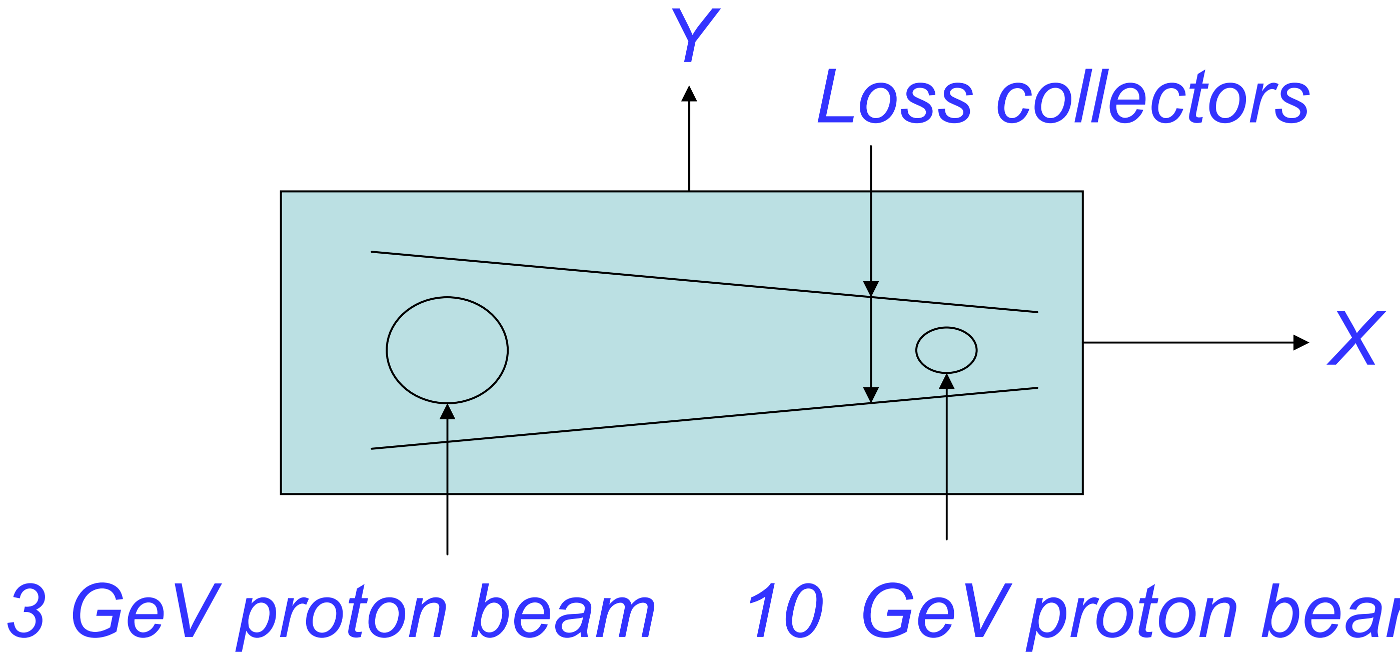


Collimator Scattering



Secondary collectors at Δμ ~20° and Δμ~160°

Vertical Collimation in FFAGs

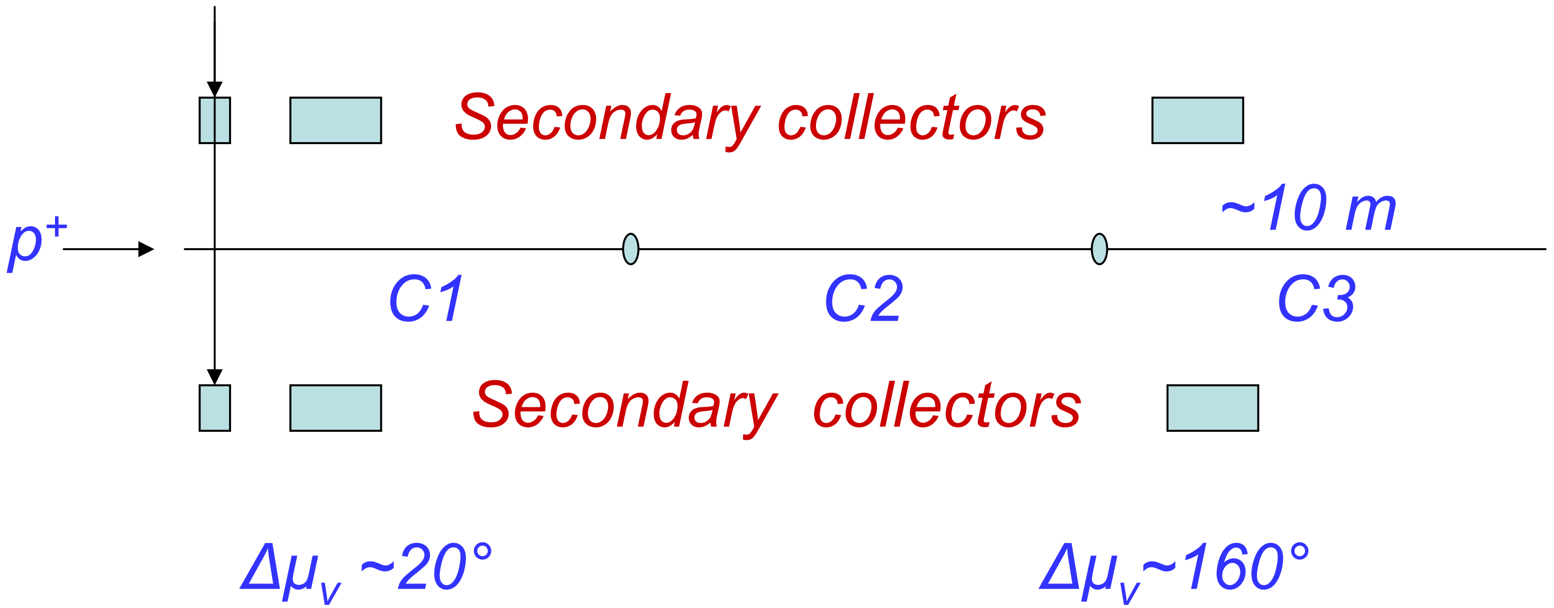


Coupling may limit horizontal growth.

Proton Driver Example

NFFAG Loss Collection Region

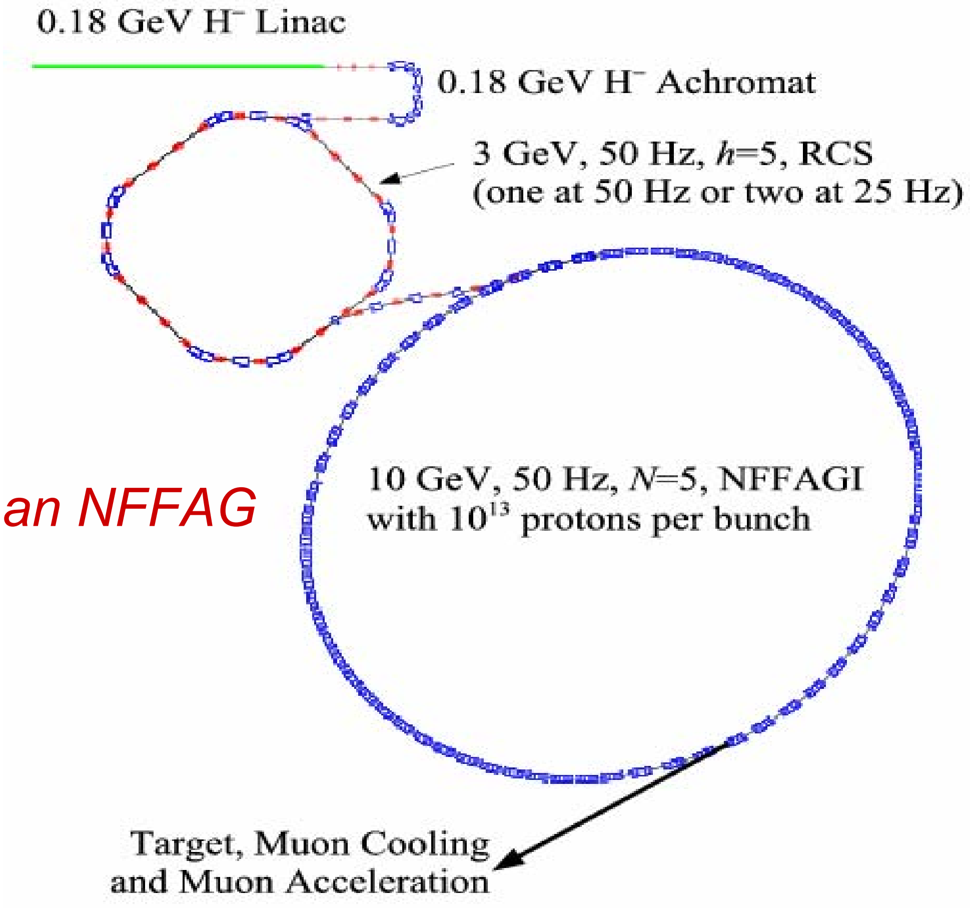
Primary collimators (upstream end of 4.4 m straight)



Direct beam loss localised in the collection region.

Beam 2.5 σ, Collimator 2.7 σ and Acceptance 4 σ.

NFFAGI Proton Driver



Now favour an NFFAG

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.

Summary For NFFAG Collectors

Vertical loss collection easier than for an RCS.

ΔP loss collection needs beam in gap kickers.

Horizontal loss collection only near ejection.

Horizontal beam collimation prior to injection.

Minimize halo growth during the acceleration.

Minimise non-linear excitations as shown next.

NFFAG Non-Linear Excitations

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

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

Use 13 such cells for the insertions of an NFFAGI.

Use (13 x 5) + 1 = 66 of such cells for an NFFAG.

IFFAGI Beam Loss Collectors

The IFFAGI $\mu^{\pm}$ rings differ from the NFFAG P driver:

- *Closed orbits are isochronous through acceleration*
- *Q_h varies over the aperture to preserve isochronism*
- *Several horizontal betatron resonances are crossed*
- *There are counter-rotating μ^{+},μ^{-} beams during cycle*
- *Muons decay to neutrinos ~ uniformly over the ring*
- *Transverse beam ε_n is an order of magnitude larger*

Any growth in ε_n results in direct $\mu^{\pm}$ beam losses.

Are IFFAGI Loss Collectors Needed?

Closed orbit deviations may give high, local $\mu^{\pm}$ losses.
These add to the heat deposited due to the $\mu^{\pm}$ decays.

The heat may be absorbed in vac. chamber cladding.
Cladding needed for whole ring if collimators not used.

Hence, use $\mu^{\pm}$ loss collimators to localise the losses.
Use a long & dedicated region for the loss collectors.

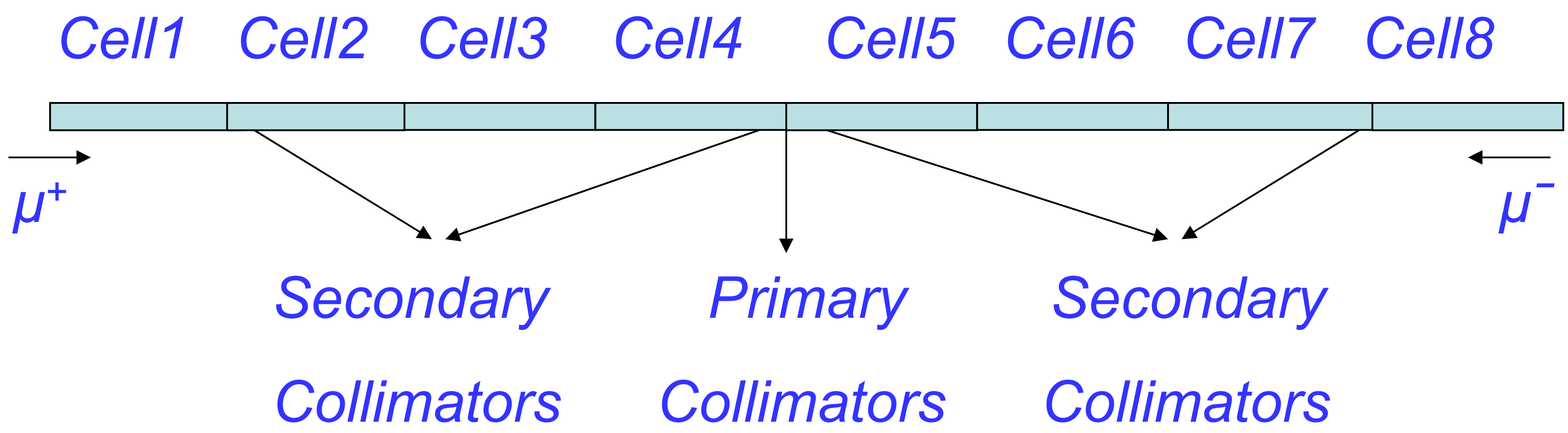
IFFAGI Insertions

Loss collection, inject/ejection benefit from insertions.
Long collection region for the counter-rotating μ^+ & μ^-.

6 adjacent cells needed, and hence an 8 cell insertion.
Use 8,18 cell superperiods for a 9.5-20 GeV $\mu^\pm$ ring.
Vertical collimation at a constant Q_v. as for NFFAGs.

No ΔP collimation by gap kickers in isochronous rings.
Any remaining beam needs removal between cycles.

Collimator Layout for $\mu^{\pm}$ IFFAGI Ring



(Local shielding around all collimators)

8 Cell Insertion in one of 8, 18 Cell Superperiods

IFFAGI Beam Power Levels

20-50 GeV, 50 Hz, combined μ^+ and μ^- ring: ≈ 4.5 MW
9.5-20 GeV, 50 Hz, combined μ^+ and μ^- ring: ≈ 1.8 MW

Peak, fundamental beam loading for 14-turn acc'n in the latter, assuming 1 input train at a time, of 80 μ^+ & 80 μ^- bunches, is:
For 5 bunch trains in total, 1.135 km circumference : ≈ 40 MW

Note: peak beam current was 48.5 larger in earlier US design:
0.400 km circumference,1 bunch train @ 15 Hz: ≈ 1940 MW

Collimators have to withstand localised losses (0.5% ≡ 9 kW)
External collimators needed to prevent any higher loss levels.

Tune choices for Re-designed IFFAGI

All 8 superperiods have 10 N & 8 I, isochronous cells.
Normal & insertion cells have constant Q_v = 0.1 & 0.16.
The insertion cells are thus always matched vertically.

Horizontal cell tunes must keep γ-t = γ and be < 1/3.
Q_h (normal cell): 0.09 to 0.25 between 9.5 and 20 GeV.
Q_h (insertion cell): 0.11 to 0.32 between 9.5 & 20 GeV.

Tracking needed to study fast resonance crossings:
Cell resonances at $Q_v = Q_h$, $2Q_v = 2Q_h$ and $2Q_v = Q_h$.
Superperiod resonances at $3Q_h$ = 40,….., 112, 120.

Notes on Muon Decay Ring Collectors

There are separate Triangle Rings for μ^+ & μ^-.
Solenoids are used in the ν production region.

There is transverse betatron collimation only.
Collectors in short straight of the triangle rings.

Use of radiation hard quadrupoles is proposed.
e^- beam dumps at end of production straights.

Notes on Collectors for RLA or DRLA

Difficult to design collectors for linac straights.

Are loss collectors needed in some/all arcs?

Need to span 6 cells if counter-rotating beams.

High normalised dispersion for ΔP collimators.

Low dispersion for x and y betatron collimators.

These add to the complexity of the arc designs.

Summary for IFFAG Collectors

Space is available in the ring lattice for $\mu^{\pm}$ collectors.
Six adjacent cells are needed for counter-rotating $\mu^{\pm}$.
There is collimation for the vertical beam loss only.

Horizontal beam collimation is made prior to injection.
Non-extracted beam is removed in-between cycles.

Further tracking studies are needed for the IFFAGI.
Crossing the cell resonance, Q_h =1/3, leads to loss.
New design of muon IFFAGI avoids this feature.