Non-isochronous and Isochronous, Non-scaling, FFAG Designs

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Non-scaling, FFAG Designs

- *Linear, nearly-isochronous, 12 turn, 10-20 Gev,* $\bullet^{\pm}$ *ring*
- *Linear, non-isochronous, MW, proton and U238 drivers*
- *Linear, non-isochronous, proton and* C^{6+} *medical rings*

- *Non-linear, isochronous, 8 turn, 8-20 GeV,* $\bullet^{\pm}$ *ring*
- *Non-linear, non-isochronous, 4 MW, 10 GeV,* H^{+} *driver*
- *Non-linear and linear, low energy, electron models*

Non-scaling, Ring Features

Scaling rings: combined function magnets, F(+) and D(–).

Non-scaling rings may have smaller orbit separations for reversed signs of bending, D(+) and F(–), (due to the F(–))

The beam orbits for the different momenta are no longer scaled replicas of one another (as a function of radius).

The magnetic fields fall off outwardly, so the bending radii and the beam dynamics are different for each beam orbit.

1. Linear, Nearly-isochronous,10-20 Gev, $\bullet^{\pm}$ ring

10-20 MeV, electron model is funded (N. Bliss conf. report).
Unusual beam dynamics in model & in ($\bullet_n$= 30 $\bullet$ mm) $\bullet^{\pm}$ ring.

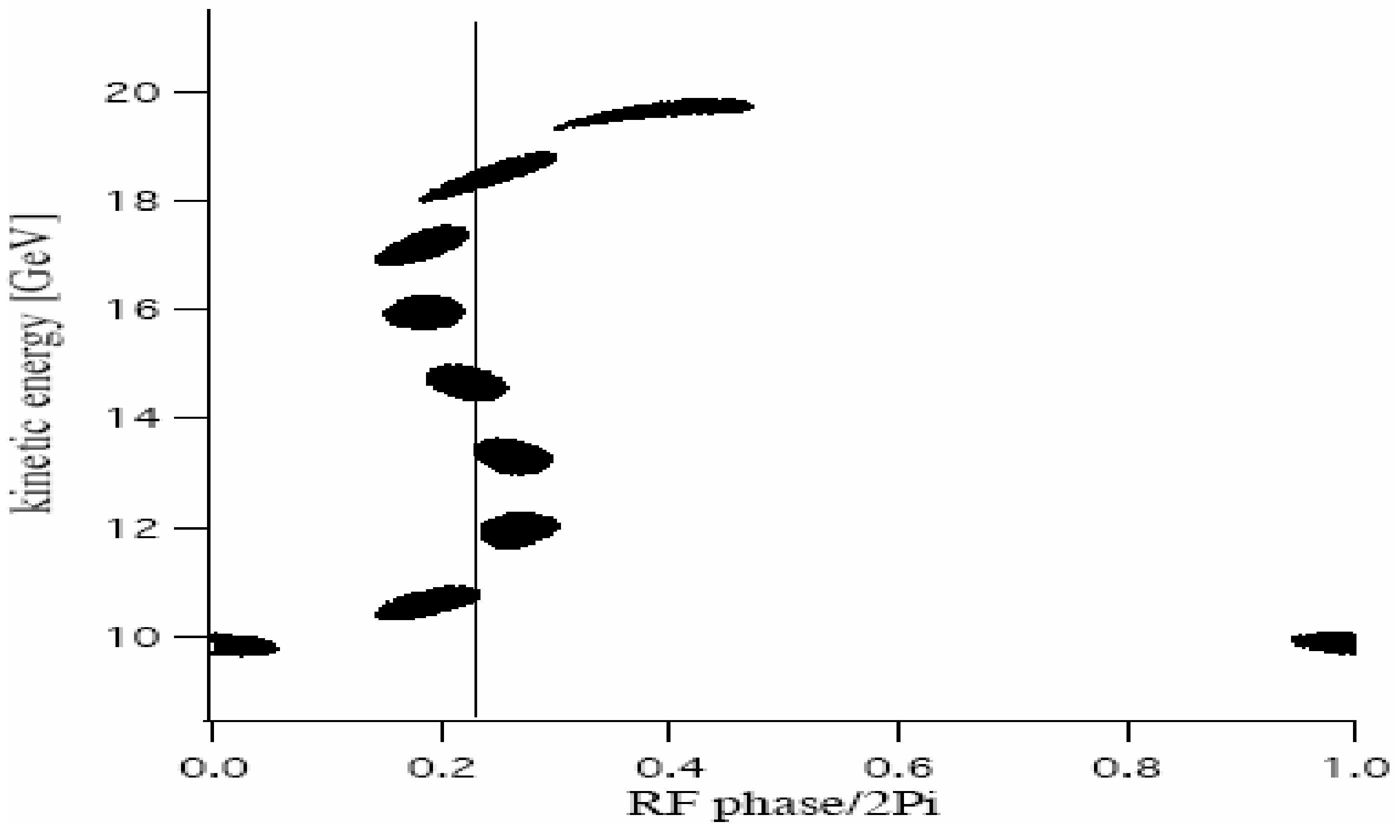
Cell betatron tunes decrease rapidly during the acceleration, and the ring betatron tunes cross many integer resonances.

The $\bullet^{\pm}$ bunches are injected outside the long term, stable region, for "gutter acceleration", non-linear, phase motion.

Nearly-isochronous motion occurs for orbits whose lengths vary quadratically with momentum, relative to a $\bullet_t$= $\bullet$ orbit.

Gutter Acceleration (201 MHz)

Bunch centroids pass the crest of cavity fields,1 or 3 times.



Simulations for Linear,10-20 Gev, •$^{\pm}$ Ring

Machida has used his s-code for tracking simulations over full momentum range, and included alignment and gradient errors.

For random, magnet position errors, the rms orbit distortions increase ••t (t = time), indicating random dipole, kick effects.

For random gradient errors, lattice function distortion of beam at the emittance-ellipse boundary shows similar, time dependence.

The probable cause is mismatching (phase space tumbling), and not the effect of the crossing of the betatron resonances.

Simulations for 10-20 Gev, •$^{\pm}$ ring (cont.)

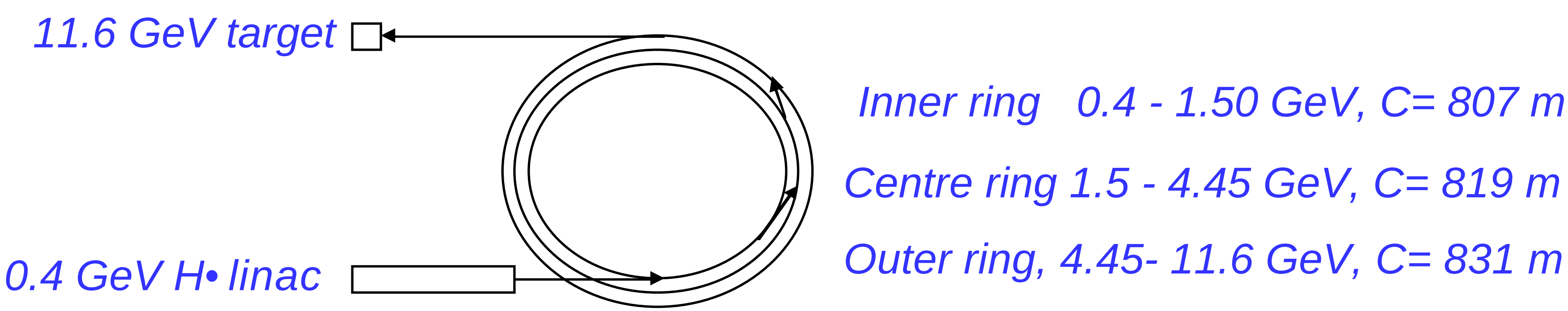
For phase motion, time of flight dependence for large transverse amplitudes results in significant longitudinal, emittance blow-up.

Remedies include raising the rf fields (to reduce number of turns) or addition of higher harmonic rf (to flat-top the composite fields).

A 5-10 GeV ring ahead of the 10-20 GeV, •$^{\pm}$ ring has now been replaced by a dog-bone RLA, to avoid the longitudinal mismatch.

Effects are due to •$_{n}$ of 30 (•) mm rad (cooling channel output), which also makes extraction very difficult (ahead of a cryostat).

2. Linear, Non-isochronous, H^+ & U Drivers



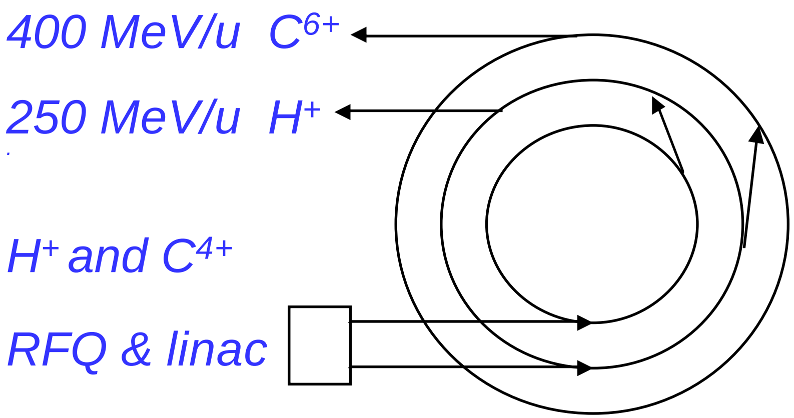
BNL, 50 Hz, 4 MW, proton driver design for a Neutrino Factory.

The beam dynamics differs from that of the 10-20 GeV, •$^{\pm}$ ring:

- *the normalised beam emittances are very much less*
- *transverse and longitudinal space charge forces occur*
- *operation is far from isochronism, with • well below •$_t$*
- *acceleration (ferrite or HNJ) is in phase stable region*

Both designs are similar, in having fast resonance crossing.

3. Linear, non-isochronous, H^+ & C^{6+} cancer rings



Inner ring H^+ *7.95 - 31 MeV, C= 34.56 m*

Centre ring H^+ *31 - 250 MeV, C= 43.20 m*

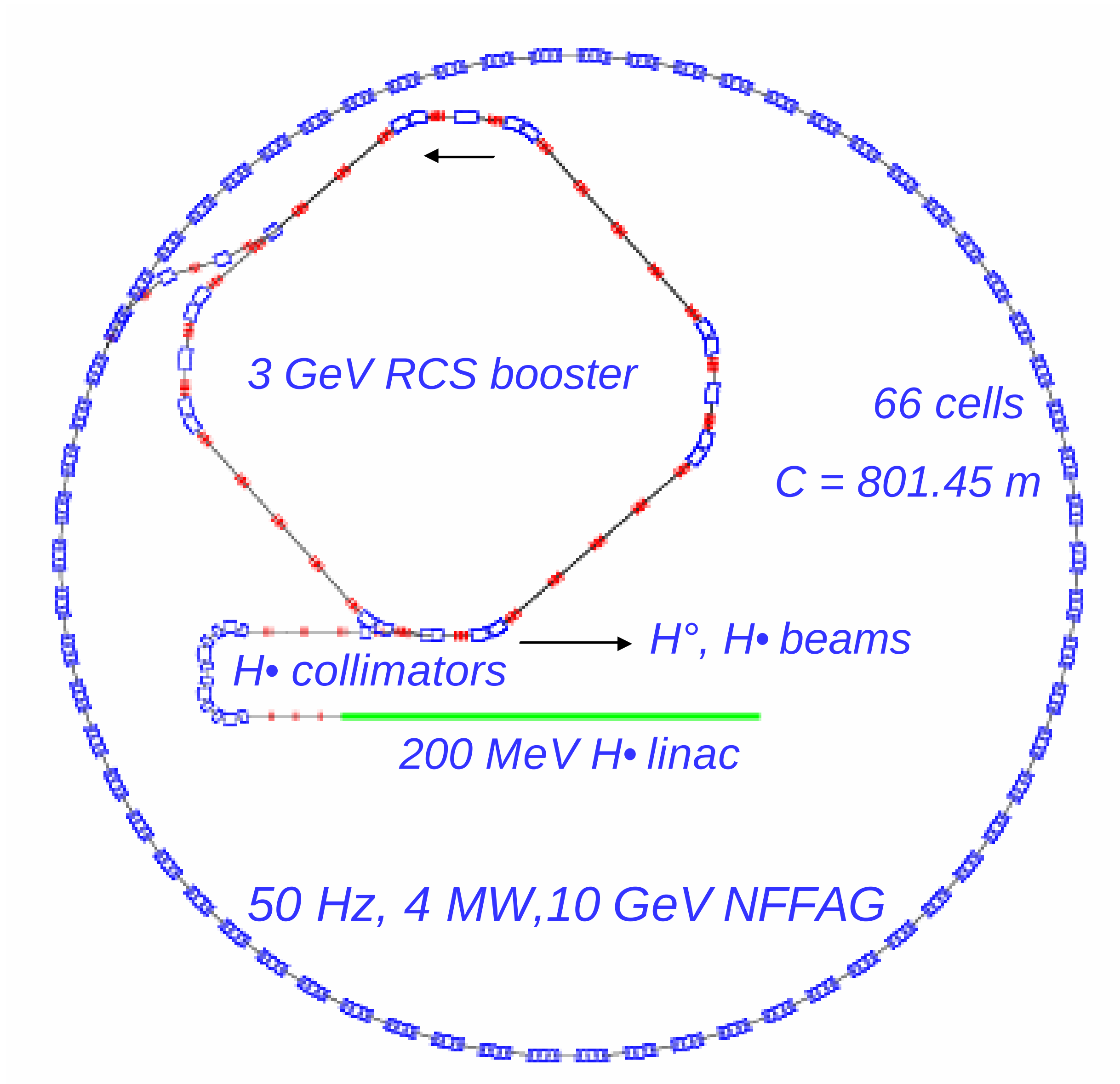
Centre ring C^{6+} *7.89 - 69 MeV/u, C= 43.20 m*

Outer ring C^{6+} *69 - 400 MeV/u, C= 51.84 m*

Three ring design (radii ratio 4:5:6) of Keil, Sessler & Trbojevic

- *Each of the rings has 36, linear, non-scaling, doublet cells*
- *Beam dynamics is similar to that of the 4 MW proton driver*
- *Rapid acceleration as the tunes cross integer resonances*
- *Harmonic number jumping, fixed frequency rf is proposed*
- *Rings 2/3 need 2.4/10.8 MV peak, respectively, at •1.3 GHz*

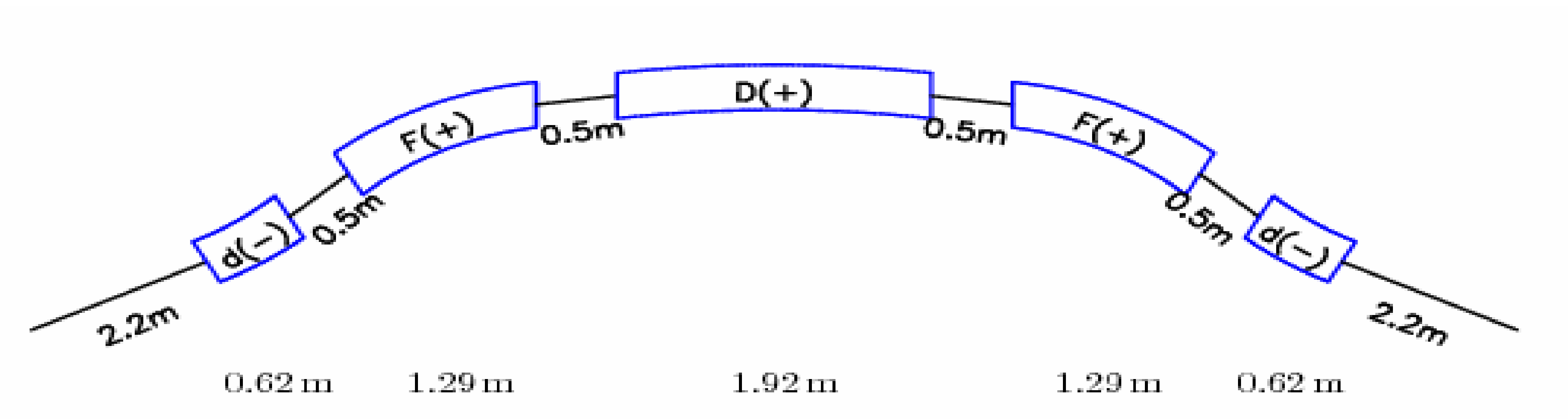
4. Neutrino Factory, Non-linear, NFFAG H^+ Driver



Non-linear, NFFAG Lattice Program

- *A linear lattice code is modified to obtain estimates of the non-linear fields in a group of FFAG magnets*
- *Bending radii are found from average field gradients between adjacent orbits and a dispersion D-function*
- *D is a weighted, averaged, normalized dispersion of new orbit relative to old, and the latter to the former*
- *First, homing routine obtains required betatron tunes. Second routine seeks exact, reference orbit closure.*
- *Accurate estimates made for reference orbit lengths. Analysis: process lattice data & ray trace in Zgoubi.*

Non-linear, Non-scaling, Lattice Pumplet Cell



O	d(-)	F(+)	D(+)	F(+)	d(-)	O
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 & angles for the 10.0 GeV, 12.143 m, NFFAG orbit.
Isochronous version (IFFAG) has different cell parameters.

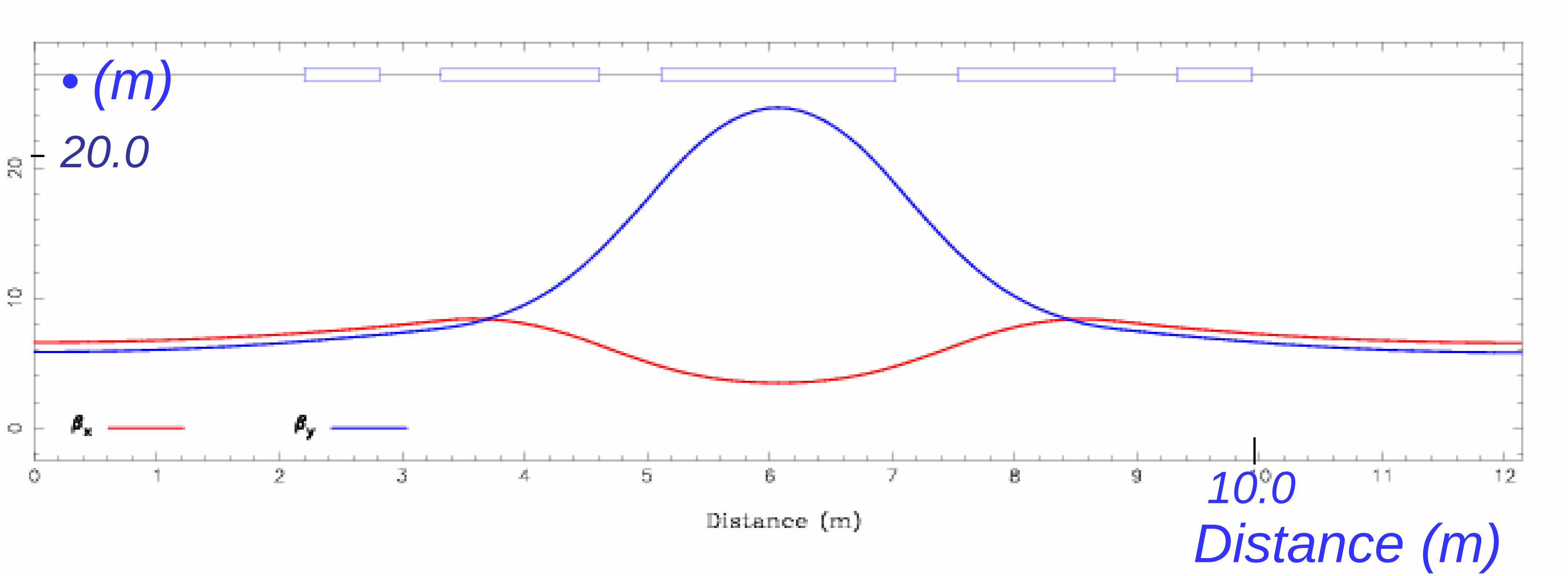
Non-linear Fields and Reference Orbits

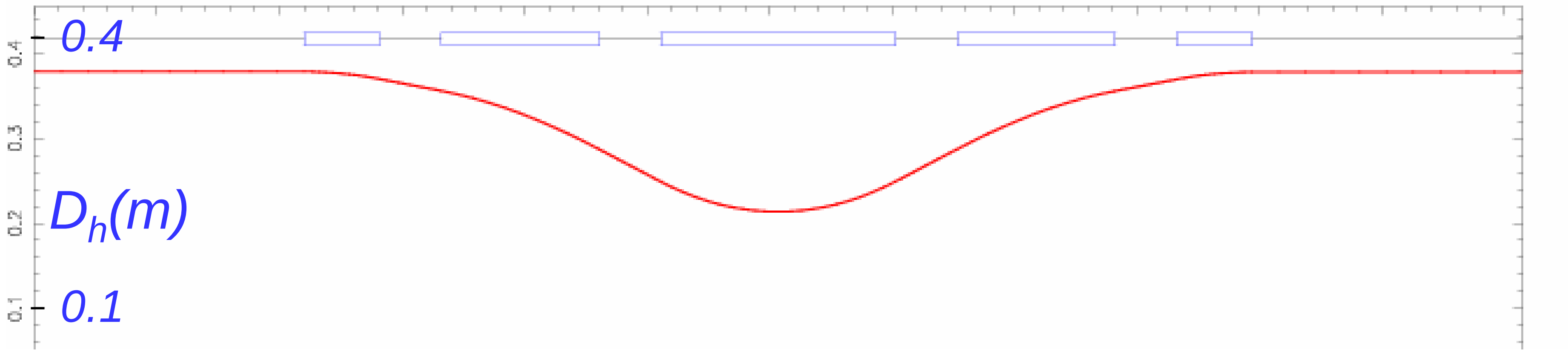
- *Low ampl. Twiss parameters are set for a max. energy cell.*
- *Successive, adjacent, lower energy reference orbits are then found, assuming linear, local changes of the field gradients.*
- *Estimates are repeated, varying the field gradients for the required tunes, until self-consistent values are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

Non-linear, Non-isochronous, 3-10 GeV NFFAG

• *Ring tune values, Q_h and Q_v:*	*20.308 and 15.231*
• *Gamma-t at 3 and 10 GeV:*	*18.93 (j) and 21.856*
• *NFFAG chromaticities:*	$\bullet_h \bullet 0$ *and* $\bullet_v \bullet 0$
• *Cell tune values,* $\bullet_h$ *and* $\bullet_v$*:*	*4/13 and 3/13*
• *Number of lattice cells:*	*66*
• *Non-linear, cell cancelling*	*65*
• *The length of each cell (m):*	*12.14*
• *Peak magnet field in T (BD)*	*1.75*
• *Freq. range (MHz, h = 24):*	*8.718-8.944*

NFFAG, 10 GeV Lattice Functions





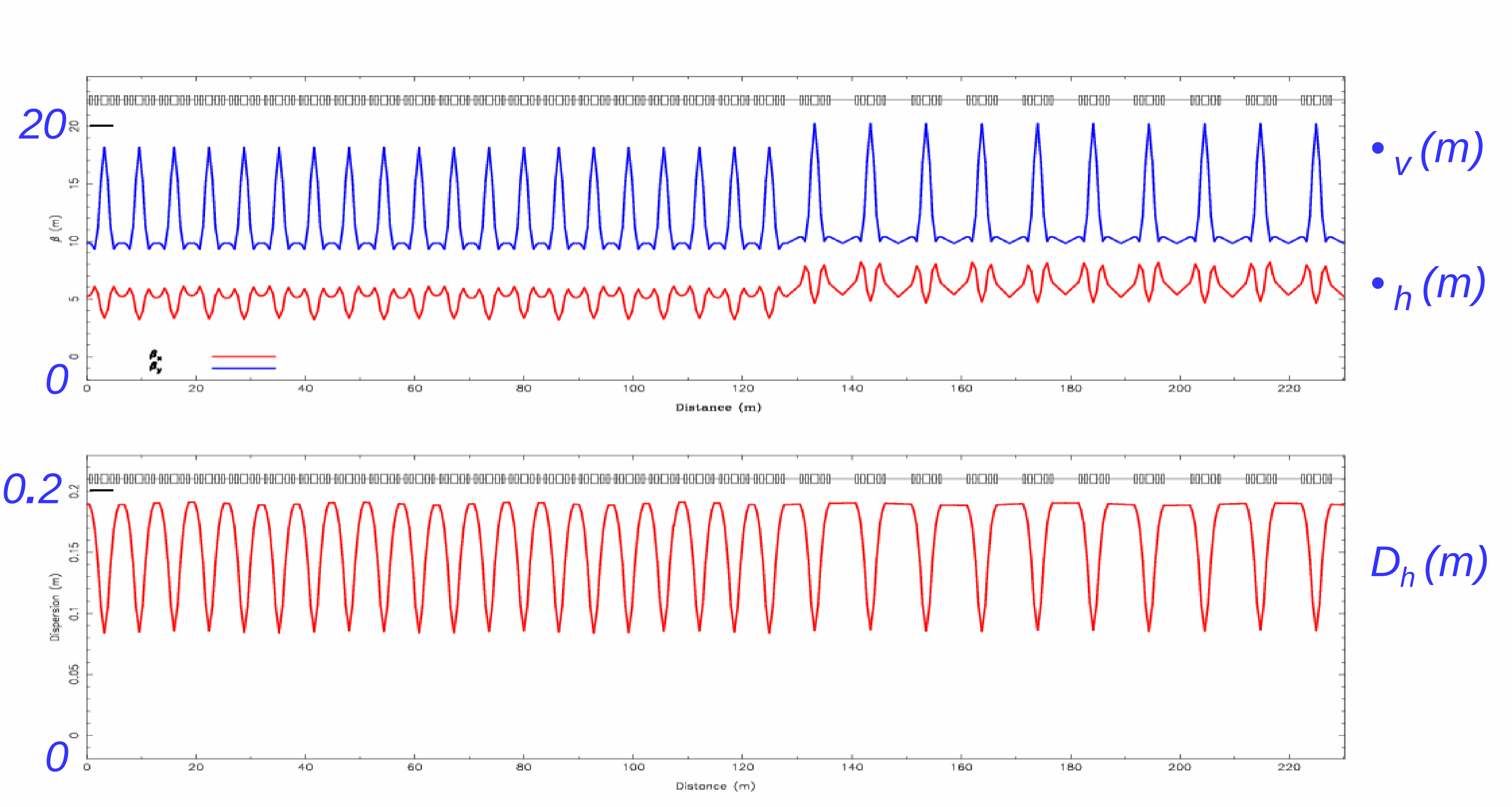
5. Non-linear, Isochronous, IFFAGI, •$^{\pm}$ Ring

- *Insertions to reduce 8-20 GeV, ring size (•$^{\pm}$ lifetime)*
- *Four superperiods of 20 normal & 10 insertion cells*
- *S-conducting combined function magnets used (5T)*
- *Modifications made to the non-linear lattice program*
- *Gamma-t made to equal • at 20 reference energies*
- *Vertical betatron tunes kept constant, Q_h has to vary*
- *Variation of tunes with large •$^{\pm}$ betatron amplitudes*

Isochronous, IFFAGI Design Criteria

- *Isochronous conditions for normal & for insertion cells*
- *Unchanged (x, x') closed orbits on adding insertions*
- *Unchanged $\bullet_v$ and $\bullet_v$ values on adding the insertions*
- *Unchanged $\bullet_h$ and $\bullet_h$ values on adding the insertions*
- *Minimise the separations of horizontal closed orbits*
- *Nine, lattice cell parameters need to be controlled*
- *Six remain, if matching at an $x\bullet = \bullet_h = \bullet_v = 0$ position*
- *Use the six variables of two, different pumplet cells*

8-20 GeV IFFAGI Lattice Functions at 14.75 GeV



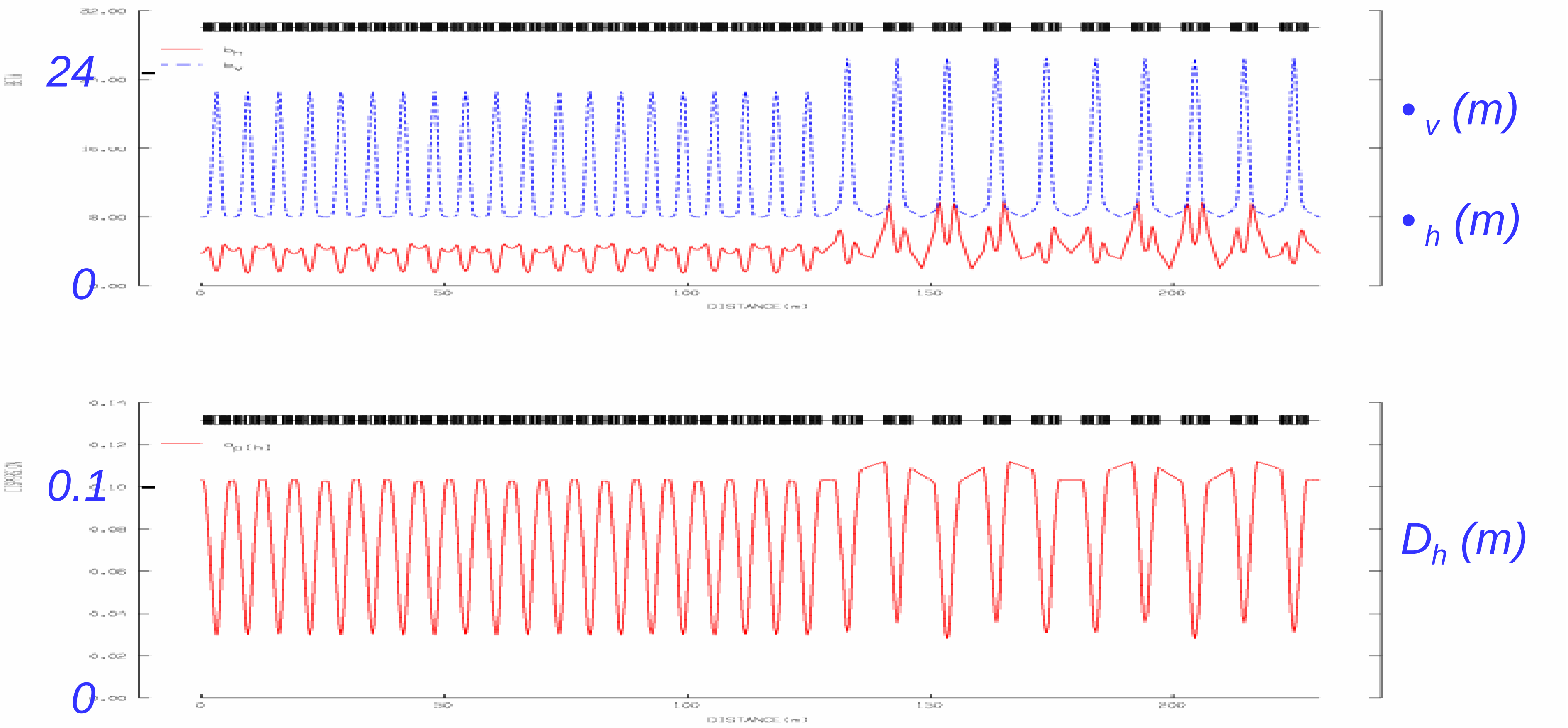
IFFAGI Reference Orbit Separations (mm)

Energy range in GeV	*9.5 to 20*	*8.75 to 20*	*8.0 to 20*
• *Long straight sections*	*181.2*	*221.8*	*269.8*
• *Insertion cell bd unit*	*180.4*	*221.2*	*269.7*
• *Insertion cell BF quad*	*164.5*	*206.6*	*267.9*
• *Insertion cell BD unit*	*106.7*	*138.1*	*177.7*

Insertion, normal cell and ring lengths = 10.2, 6.4 and 920.0 m.
Eight-turn, isochronous acceleration, with 1.5 GeV gain / turn.
Small, acceptable ripple for $\bullet_h$ (max) occurs at most energies.

Studies req'd to identify loss mechanisms for large emittances

8-20 GeV IFFAGI Lattice Functions at 20 GeV



Summary

- *Steady progress is being made in the understanding of the various, linear and non-linear, non-scaling FFAG designs*
- *Applications include high power proton & ion drivers, medical rings & gantries, & rapid acceleration of high energy muons*
- *Each of the non-scaling, ring designs needs a small electron model to advance its design and to prove its viability*
- *Some practical issues remain to be addressed, including the designs of the acceleration, injection and extraction systems*