# Summary
# FFAG for proton acceleration

FFAG2006, May 15th -19th

Y. Mori

# Why Proton Driver is needed?

- As Intense Source of Secondary Particles
  - Neutron
    - Spallation Neutron Source, ADSR, BNCT
  - Pion/Muon/Neutrino, Kaon, Anti-proton
    - Neutrino Factory, Kaon/p-bar Factory
  - Radio Isotope(Unstable Nuclei)
    - Nuclear Physics for proton/neutron riched nuclei

# How we can produce seconadry particles?

- Proton Beam with External Target
  - Large beam current
    - Beam loss concern (<1W/m)
    - Beam loading, space charge, radiation safety, maintenance ability
  - Target
    - cooling, shockwave, radiation damege
- Proton Beam with Internal Target
  - Ordinary scheme   poor efficiency
    - multiple(Rutherford) scattering, Straggling Emittance growth
  - New idea: ERIT(Emittance/Energy Recovery Internal Target)
    - ionization (ring) cooling

# Presentations
# FFAG for Proton Driver

- High Power Proton Driver with External Target
  - T.Roser (BNL)
  - Y.Mori(Kyoto Univ.)
  - G.Rees(CCLRC/ASTeC)
  - A.G.Ruggiero(BNL)
- High Power Proton Driver with Internal Target
  - Y.Mori(Kyoto Univ.)
  - K.Okabe(Kyoto Univ.)

# Presentations
# various issues (rf-gymnastics, optics, beam dynamics)

- Fast Bunching Experiment at 150MeV FFAG
  - M.Aiba(Kyoto Univ.)
- Multiple Resonance Crossing in Non-Scaling FFAG
  - S.Y.Lee(S.Machida)(CCLRC/AsTeC)
- Electron Mode for Proton Acceleration
  - A.G.Ruggiero(BNL)

# Needs for High-Intensity Hadron Drivers
T.Roser (BNL)

## Design options for high power facilities

| | design: | issues/challenges: |
|---|---|---|
| CW or high DF: | Cyclotron + p source | $E \leq 1$ GeV |
| | SC Linac + p source | CW front end (RFQ, DTL) |
| Low DF: | Linac + accum. ring | $E \leq 5$ (8?) GeV ($H^-$ stripping) |
| | Linac + RCS | Rep. rate < 100 Hz, $P_{RSC}/P_{Linac} \leq 10$ |
| | Linac + FFAG | Rep. rate ≤ 1 kHz, $P_{RSC}/P_{FFAG} \leq 3$ |
| | Linac + n × RCS | For high energy |
| | | Bunch-to-bucket transfers |
| | | High gradient, low frequency rf |

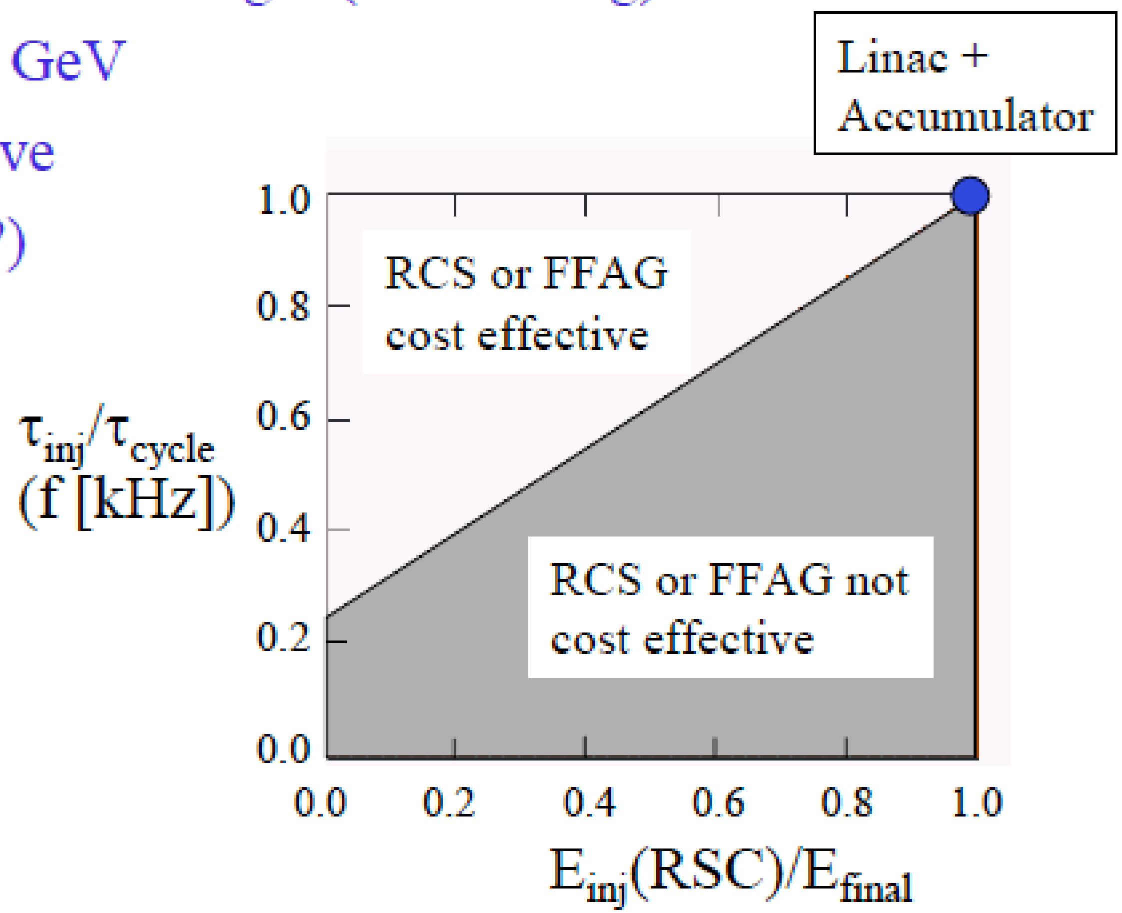
# Low Duty Factor Facilities – Accumulator vs. RCS/FFAG

| | |
|---|---|
| Linac + accum. ring | $E \leq 5$ (8?) GeV ($H^-$ stripping) |
| Linac + RCS | Rep. rate < 100 Hz, $P_{RCS}/P_{Linac} \leq 10$ |
| Linac + FFAG | Rep. rate ≤ 1 kHz, $P_{FFAG}/P_{Linac} \leq 3$ |

Maximum beam power if cost scales with total length (linac + ring):

For 1 ms linac pulse length and $E_{final} \sim 5$ GeV

→ Accumulator ring is more cost effective
unless rep. rate > 200 Hz (→ FFAG ?)



# FFAG hadron driver

Renewed interest in Fixed Field Alternate Gradient (FFAG) accelerators

Advantages: High repetition rate (~ kHz), final energy > 1 GeV

Successful demonstration of scaling (fixed tune)

Non-scaling designs with small tune variation are being developed

Example: 1 GeV, 10 mA , 10 MW, 1 kHz

After FFAG: DF: ~ $3 \times 10^{-4}$, $I_{peak}$ ~ 30 A

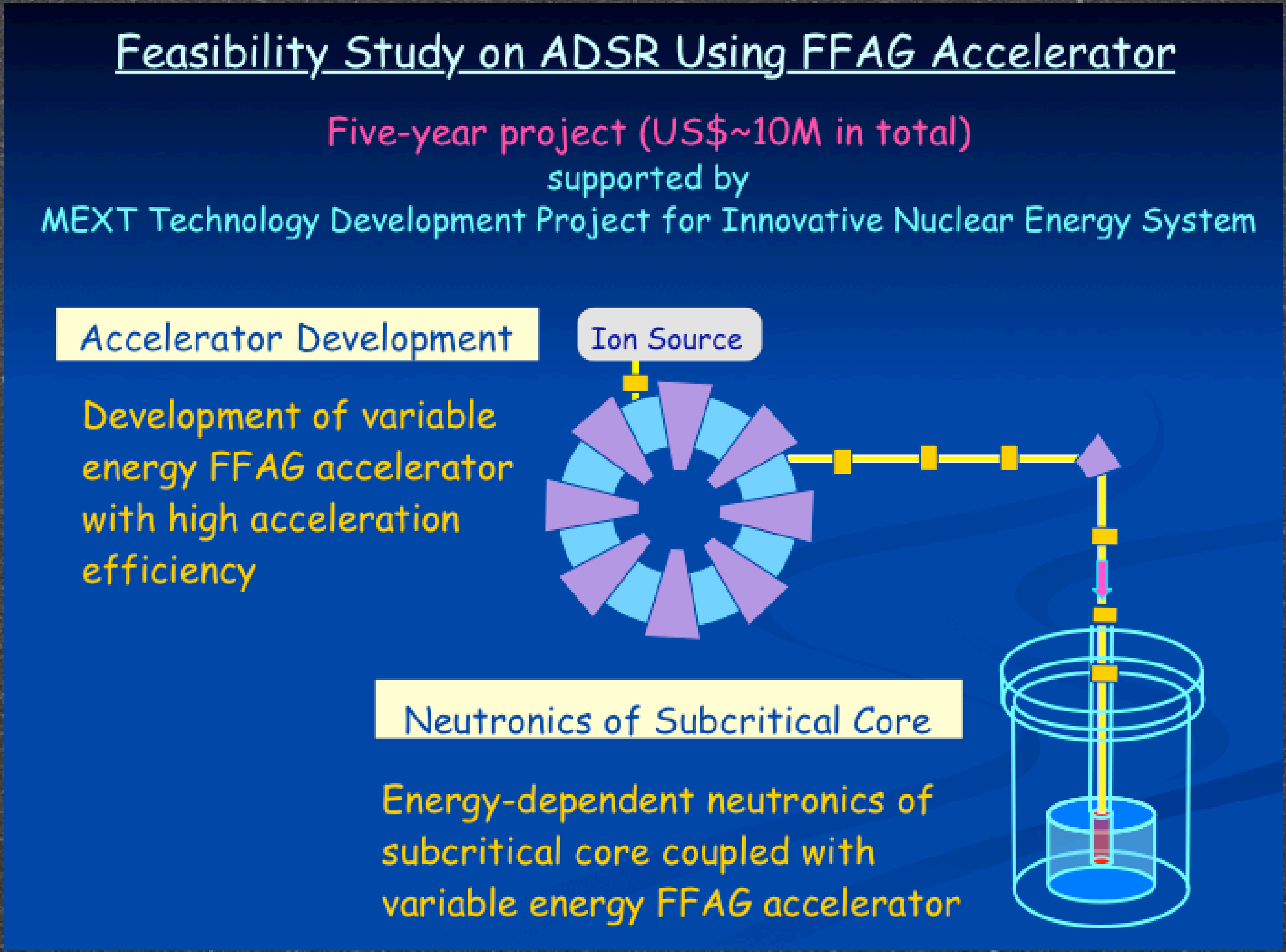
Issues: High rf gradient (> 3 MV/turn !!),

Fast frequency tuning ( ~ 0.5ms) or harmonic number hopping

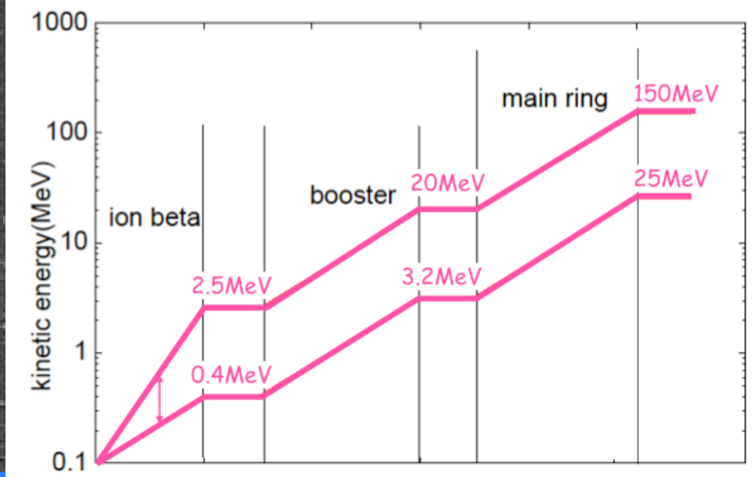
# FFAG Work in Japan for Hadron Beams

-Proton Driver with FFAG for ADS

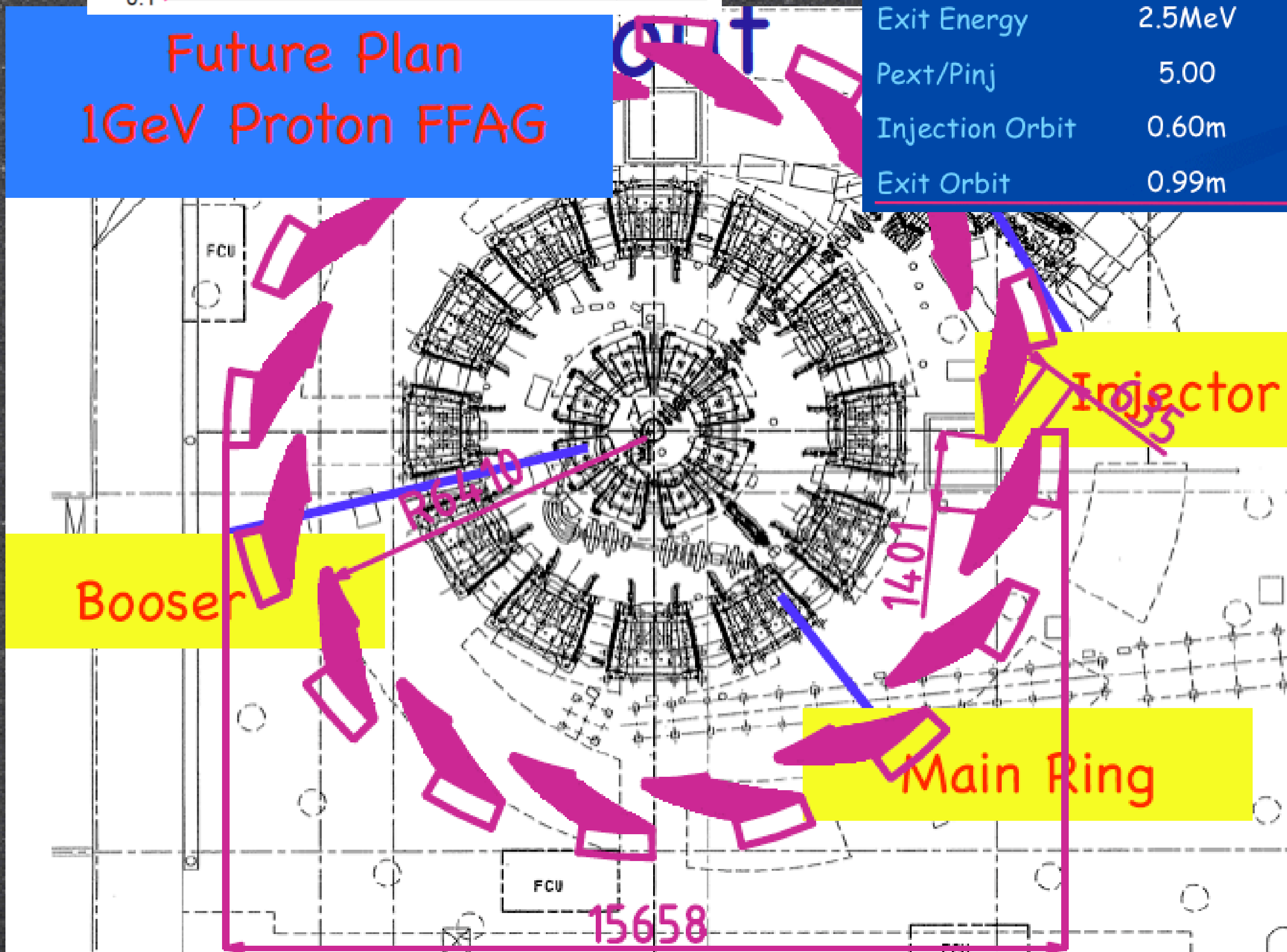
Y.Mori(Kyoto Univ.)



# Future Plan
# 1GeV Proton FFAG




| | Ion Beta | Booster | Main Ring |
|---|---|---|---|
| Focusing | Spiral | Radial DFD | Radial DFD |
| Acceleration | Induction | RF | RF |
| Number of Cells | 8 | 8 | 12 |
| k-value | 2.5 | 4.5 | 7.6 |
| Injection Energy | 100keV | 2.5MeV | 20MeV |
| Exit Energy | 2.5MeV | 20MeV | 150MeV |
| Pext/Pinj | 5.00 | 2.84 | 2.83 |
| Injection Orbit | 0.60m | 1.42m | 4.54m |
| Exit Orbit | 0.99m | 1.71m | 5.12m |



# NFFAGI and IFFAGI Loss Collectors
G.Rees(CCLRC/ASTeC)

## 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.*

## 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 $\gamma$-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*

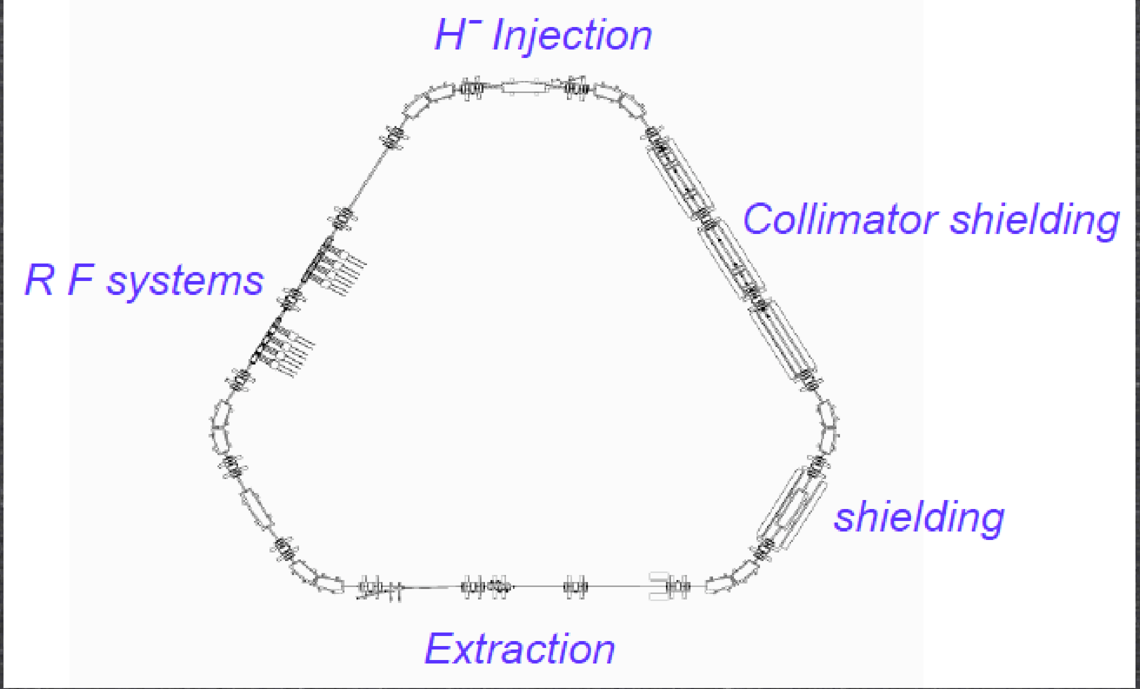
# Beam Collimation

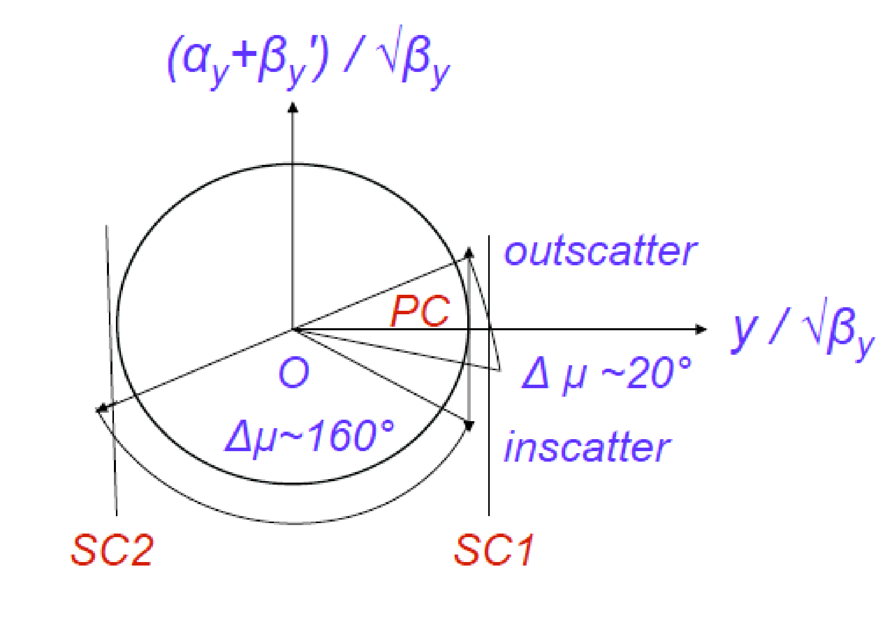
*RCS: Betatron collimation in a zero dispersion region.*
*Momentum collimation at high norm. dispersion.*

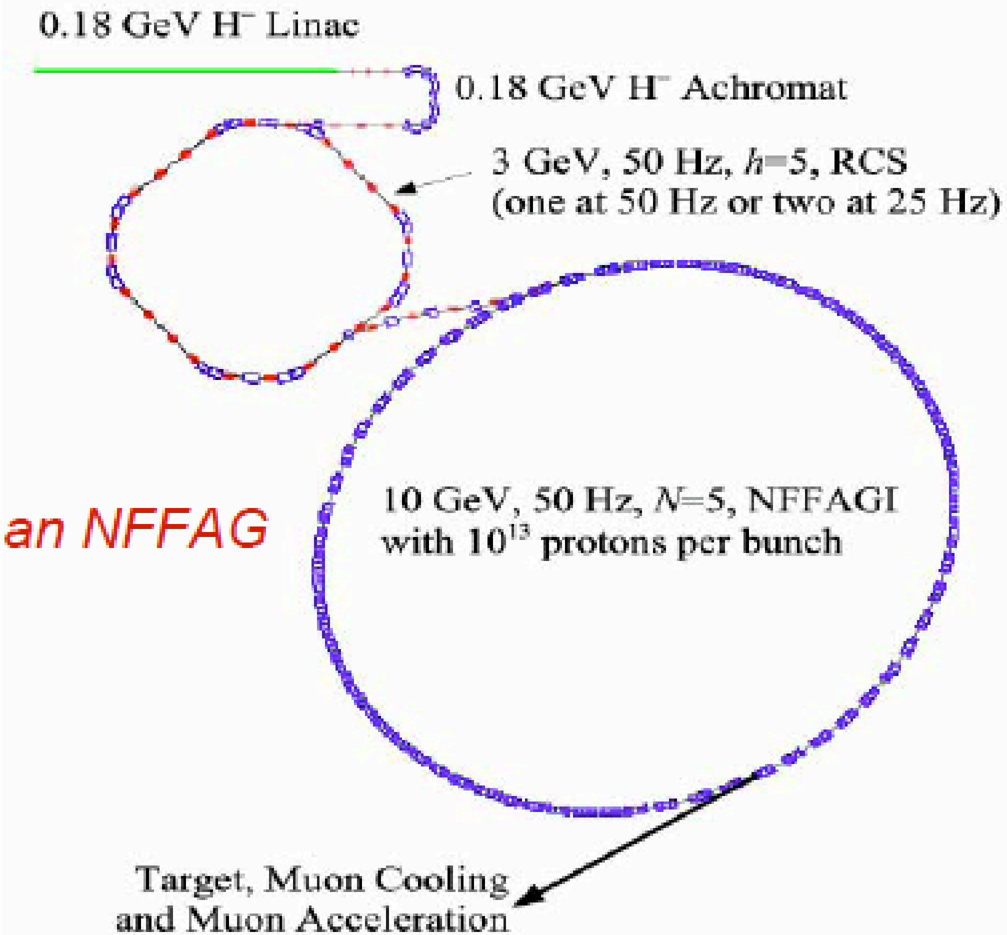
*NFFAG: V betatron collection in low dispersion areas.*
*Momentum growth limited by beam in gap kicker.*

*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.*





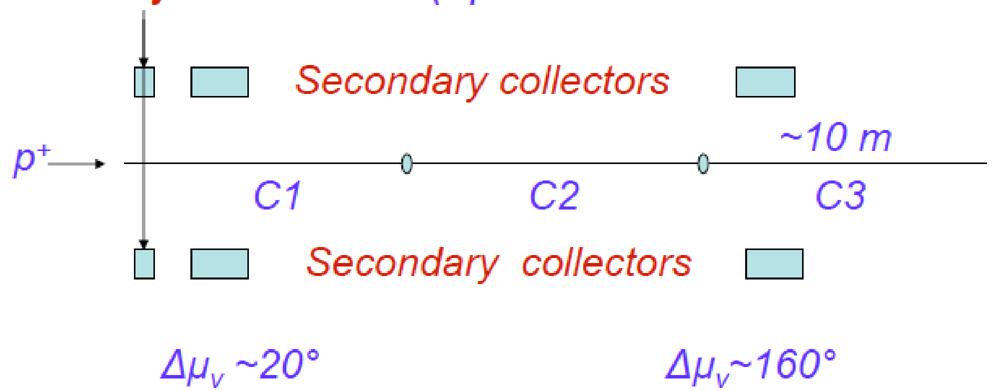

*Now favour an NFFAG*

dynamic aperture?

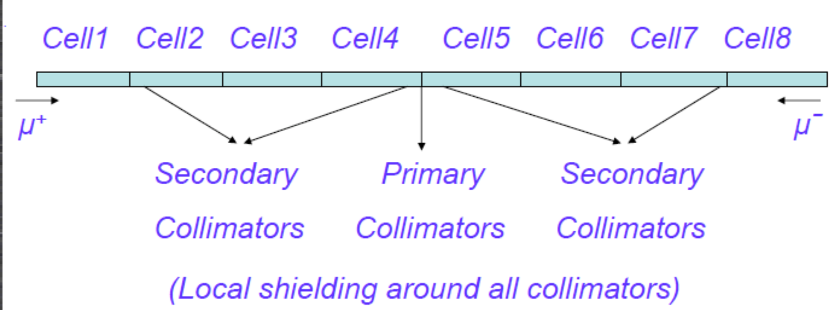
*Vertical loss collection easier than for an RCS.*
*ΔP loss collection needs beam in gap kickers.*
*Horizontal loss collection only near ejection.*

*Horizontal beam collimation prior to injection.*
*Minimize halo growth during the acceleration.*
*Minimise non-linear excitations as shown next.*

*Primary collimators (upstream end of 4.4 m straight)*



# IFFAGI muon(+-) ring




20-50 GeV, 50 Hz, combined $\mu^+$ and $\mu^-$ ring: ≈ 4.5 MW
9.5-20 GeV, 50 Hz, combined $\mu^+$ and $\mu^-$ 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 $\mu^+$ & 80 $\mu^-$ 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.

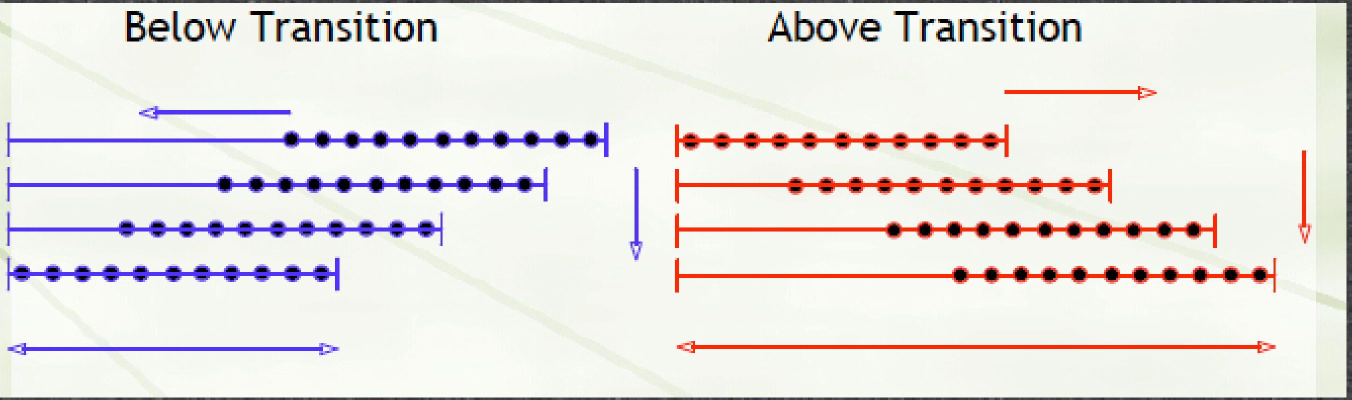
Vertical loss collection easier than for an RCS.
ΔP loss collection needs beam in gap kickers.
Horizontal loss collection only near ejection.

Horizontal beam collimation prior to injection.
Minimize halo growth during the acceleration.
Minimise non-linear excitations as shown next.

# BNL NonScaling FFAG Works for Hadron Beams A.G.Ruggiero(BNL)

- Design of a Proton FFAG Accelerator
- FFAG Accelerator for AGS Upgrade
- 1-GeV 10-MW FFAG Proton Driver
- FFAG Proton Driver for Neutrino Factory
- FFAG Medical Accelerator
- e-RHIC
- FFAG for Synchrotron Light Source
- FFAG Electron Model (for Protons)
- Acceleration by Harmonic-Number Jump
- RIA

# Harmonic jump rf acceleration




**Two Programming Methods:**

1. Constant RF Phase $\phi_n$

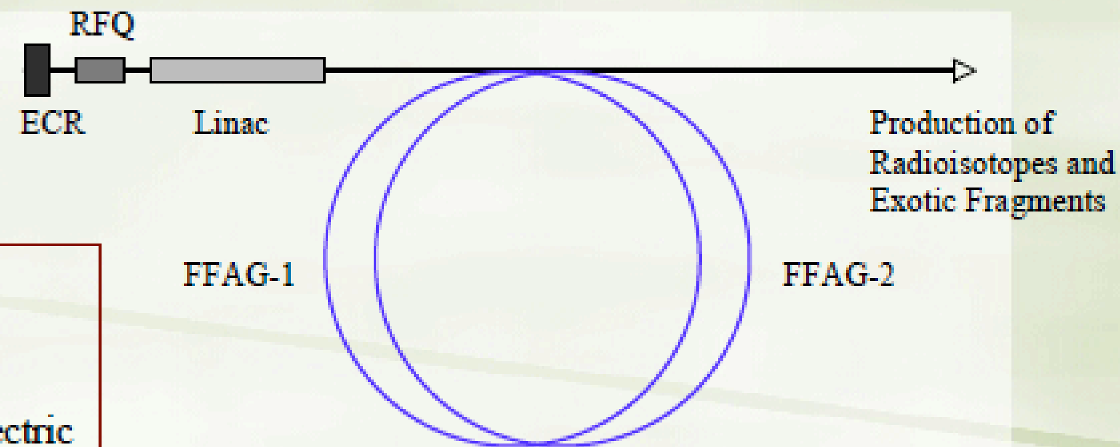
   It requires the design of a RF Cavity with proper radial field profile

2. Constant average axial Field $\xi_n$

   It requires a RF phase modulation

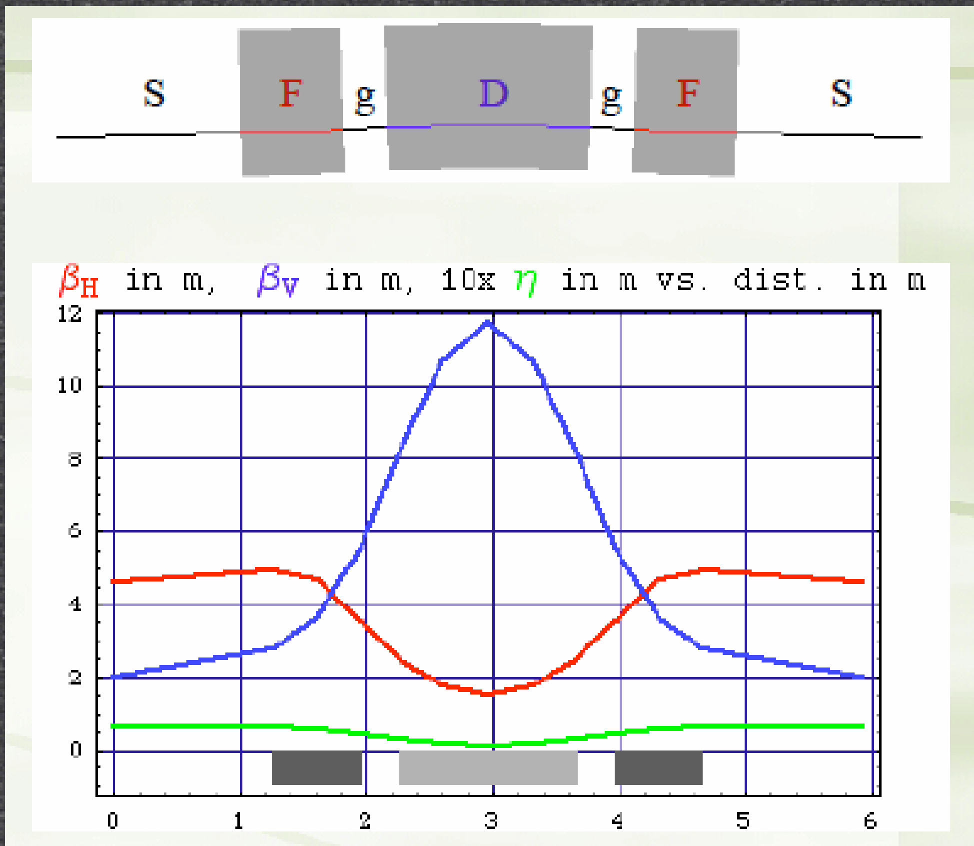
3. $f_1$ & $f_2$ mixed : Palmer(Kolomenski)

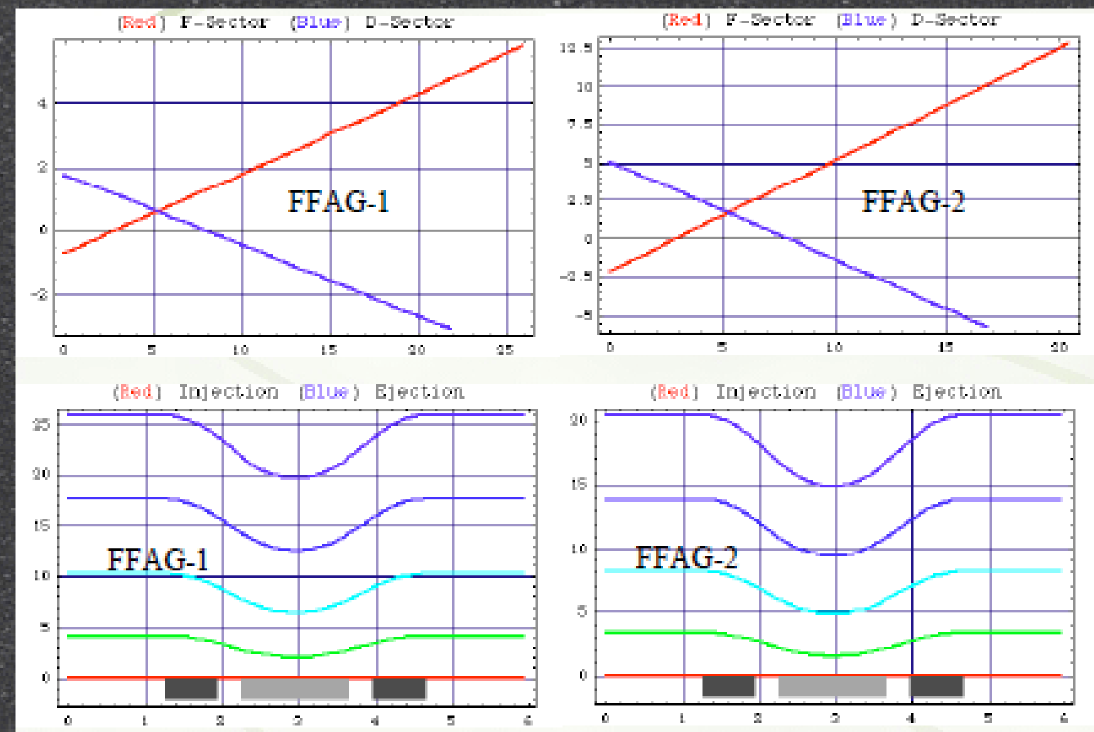
# Outline of the Scheme

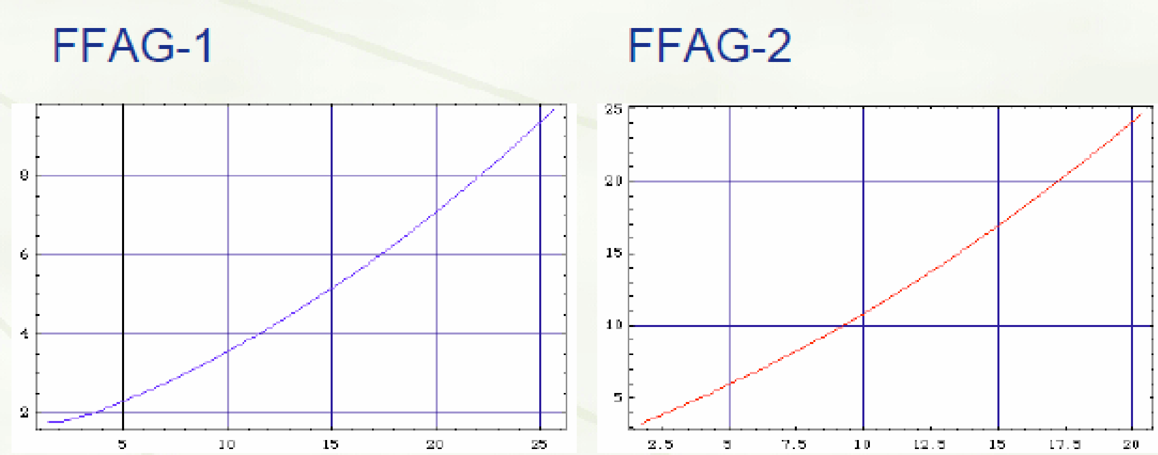



| | |
|---|---|
| Type of Ions | Uramium |
| Charge State, Q | +28 |
| Mass Number, A | 238 |
| ECR current | 30 mA-electric |
| Injector Linac Energy | 6 MeV/u |
| Beam Bunching Frequency | 201.34 MHz |
| Chopping Ratio | 80% |
| Transmission Efficiency | 80% |
| Injected Current | 20 mA-electric |
| Linac Pulse Length | 4.13 μs |
| Repetition Rate | 1,000 pulses/s |
| Linac Duty Cycle | 0.413 % |
| No. of Injected Turns | 1 |
| No. of Ions / Cycle | $1.8 \times 10^{10}$ |
| No. of Bunches | 831 |
| No. of Ions/Bunch | $2.13 \times 10^{7}$ |
| Norm. Emittance (full) | 5.0 π mm-mrad |
| Bunch Area (full) | 10 μeV/u-s |

| | FFAG-1 | | FFAG-2 |
|---|---|---|---|
| | **Inject.** | **Transfer** | **Extract.** |
| Circumference, m | 807.091 | 808.304 | 809.201 |
| Energy, MeV/u | 6 | 50 | 300 |
| β | 0.1126 | 0.3140 | 0.6526 |
| Rev. Freq., MHz | 0.0418 | 0.1165 | 0.2422 |
| Rev. Period, μs | 23.919 | 8.585 | 4.129 |
| Harmonic No. | 4816 | 1729 | 831 |
| ΔE/ Cavity, MeV/u | 0.0201 | 0.494 | 3.301 |
| Circ. Current, mA-e | 3.31 | 9.23 | 19.20 |
| RF Power, MW | 0.0159 | 1.087 | 15.08 |
| Beam Power, kW | 4.04 | 33.69 | 202.15 |
| Bunching Factor | 4 | 8 | 16 |
| S. C. Tune-Shift | 0.29 | 0.068 | 0.020 |


S F g D g F S
βH in m, βV in m, 10x η in m vs. dist. in m


(Red) F-Sector (Blue) D-Sector
FFAG-1
(Red) F-Sector (Blue) D-Sector
FFAG-2
(Red) Injection (Blue) Ejection
FFAG-1
(Red) Injection (Blue) Ejection
FFAG-2



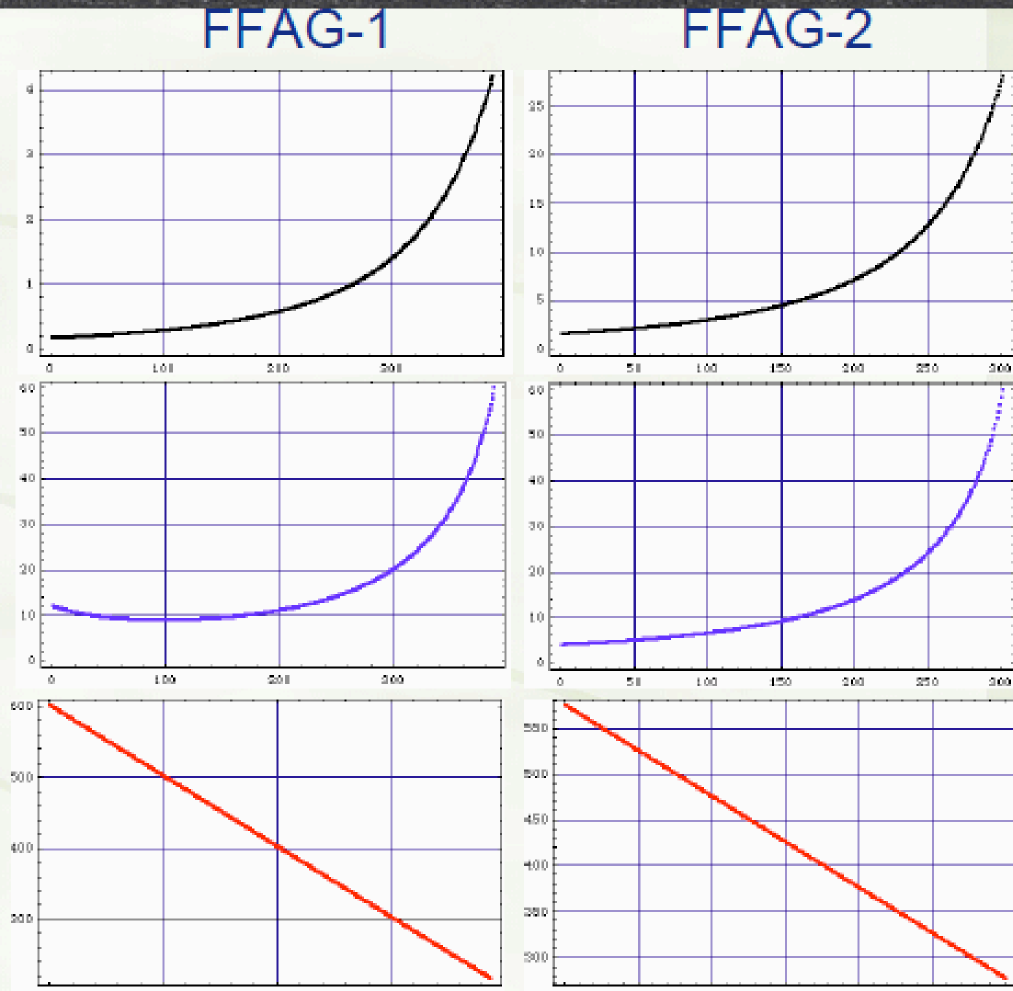

cavity voltage/
position
@constant phase

$\Delta E_n$ in MeV/u

$\phi_n$ in degrees

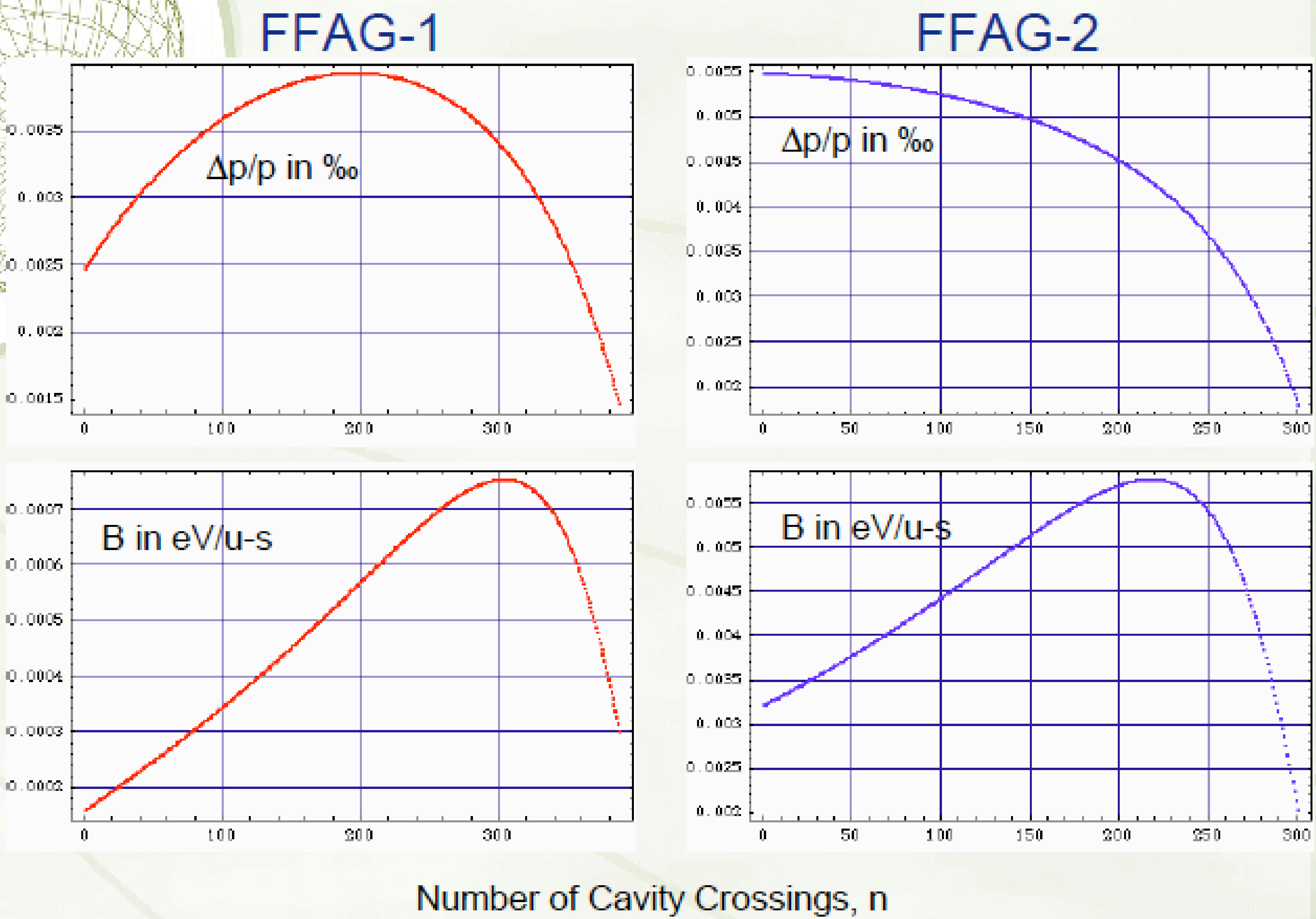
$h_n$

vs. no. of cavity crossings n




acceleration
by HNJ

# RF Buckets Height and Area




Longitudinal acceptance has to be looked at by beam tracking!

# Development of FFAG-ERIT

K.Okabe, Y.Mori (Kyoto Univ.)

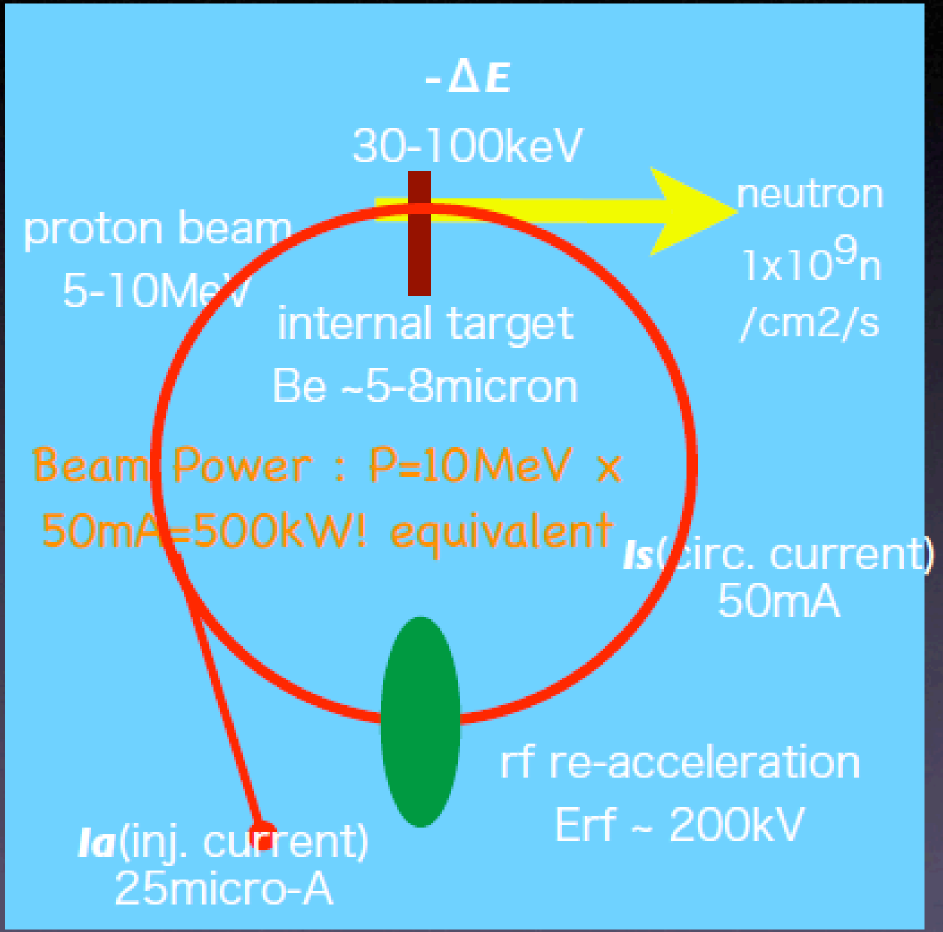
## Neutron Source with FFAG-ERIT

Emittance-energy Recovery Internal Target

- Proton driver
  - another concept
- FFAG-ERIT scheme
  - internal target
  - energy loss
    - recovered by rf
  - emittance growth
    - ionization cooling
  - large acceptance
    - FFAG(scaling)
  - target
    - heat loss 1kW

Project approved 2005-2007

Under Construction

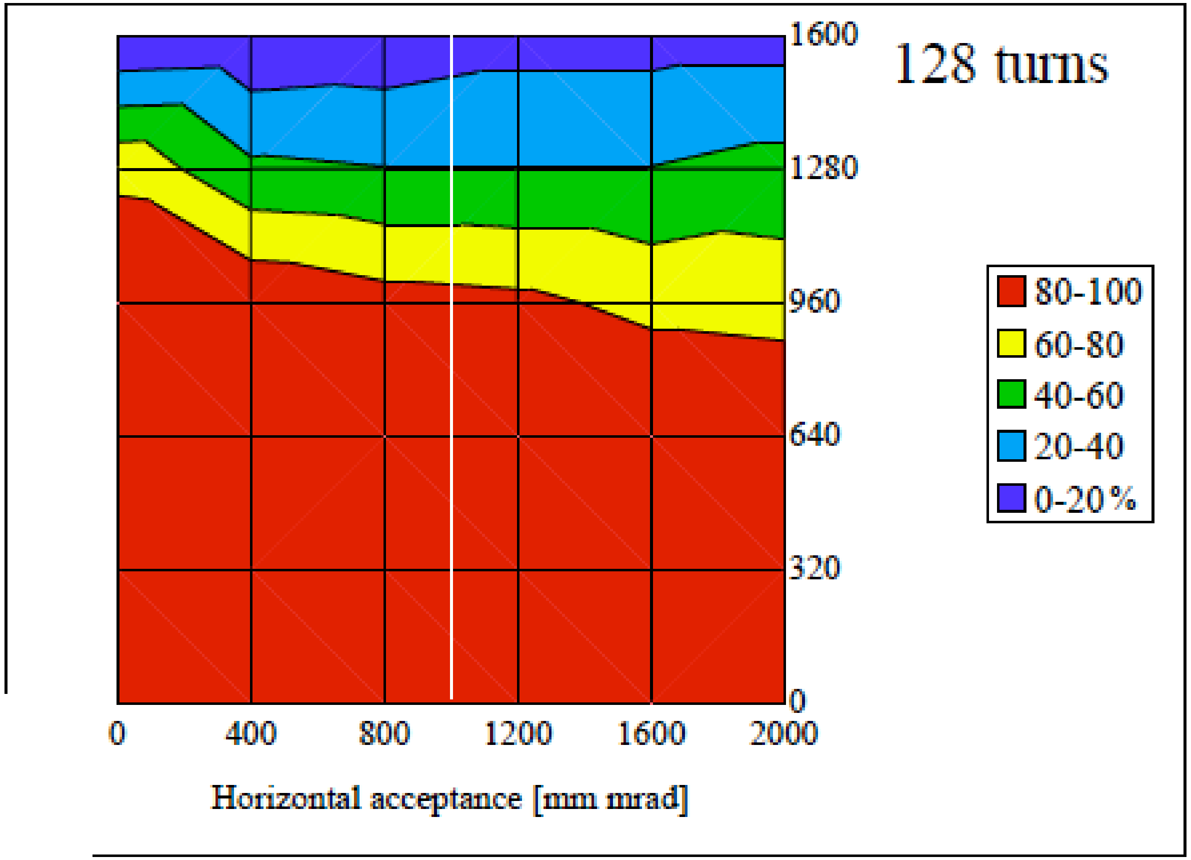



Beam Power ~0.5MW

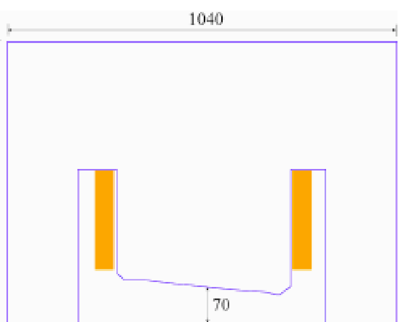
# 4D acceptance study

When the particle has amplitudes both the horizontal and vertical axis, the acceptance becomes small in the effect.

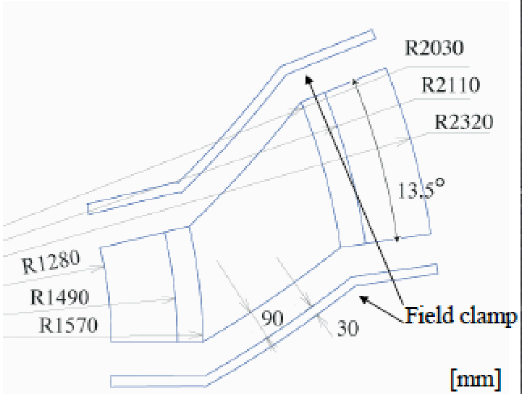
The target value(1000 [π mm mrad]) is almost achieved.




k value = 1.7
Half gap = 70 [mm] @10MeV
$r_0$ = 1.8 [m] : ~7250 [G]
MMF ~ 42000 [Ampere turns]
Current density ~ 7.4 [A/mm$^2$]
(Effective coil area 65%)



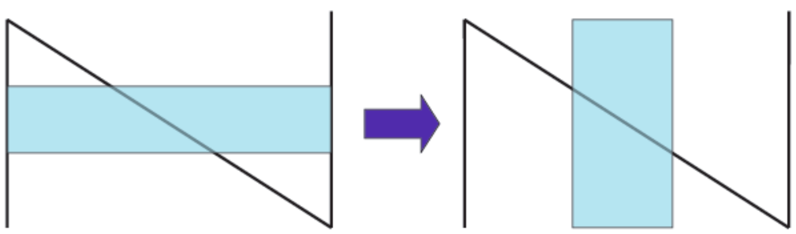

Spiral sector type
Sector num. = 8
Spiral ang. = 35 [deg]
$r_0$ = 1800 [mm]
Opening ang. = 13.5 [deg]



# Fast Bunching Experiment at 150MeV FFAG

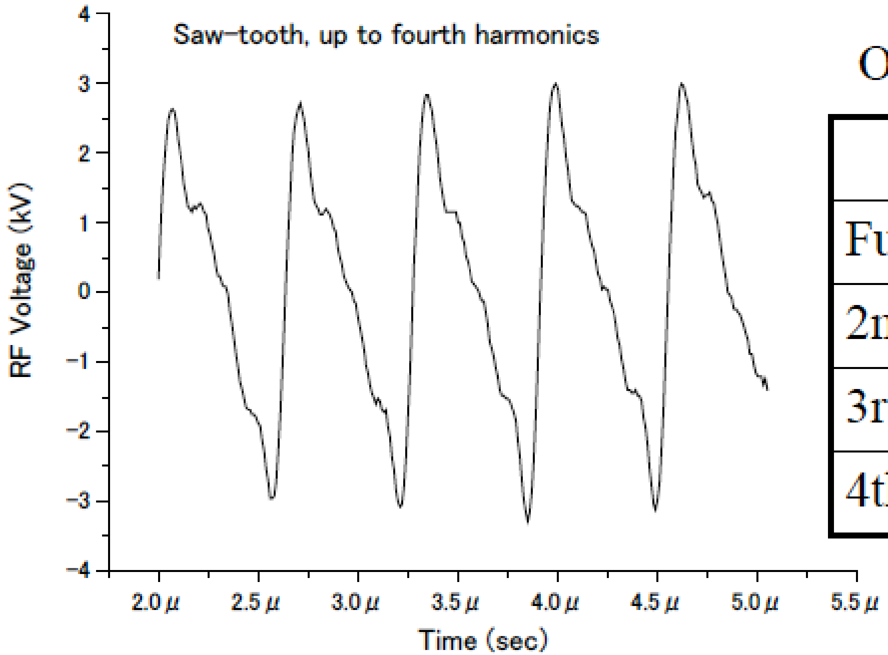
M.Aiba(Kyoto Univ.)

## Fast Bunching with Saw-tooth



## Saw-tooth

Fourier Expansion: $V(t) = \frac{2}{\pi} \sum_{1}^{\infty} (-1)^{n-1} \frac{1}{n} \sin(2\pi n f_{rev} t)$




Optimization of law-level

| | Amp. | Phase |
|---|---|---|
| Fund. | 100% | 0 |
| 2nd. | 63% | 0 |
| 3rd. | 63% | -60deg. |
| 4th | 100% | -90deg. |

Saw-tooth wave is formed well with up to fourth harmonics.

# Fast Bunching Experiment at 150MeV FFAG

beam capture
~20% increaed.

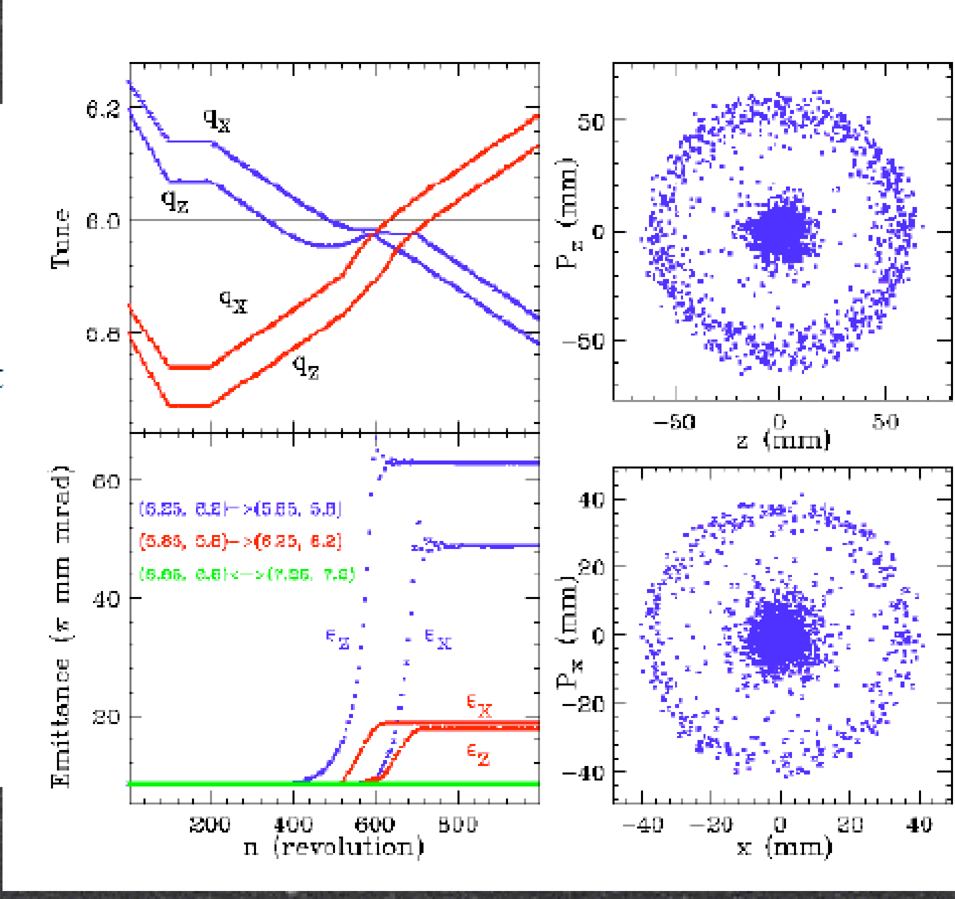
# Multiple resonance Crossing in Non-Scaling FFAG

S.Y.Lee(S.Machida)(CCLRC/AsTeC)

- Space charge tune spread affects resonance crossing.

1. Systematic Nonlinear space charge resonances can be important in high intensity accelerators
2. For future neutron source design, one should try to avoid the systematic nonlinear space charge resonance, if it is possible!
3. For the non-scaling FFAG, the nonlinear resonances induced by the space charge potential can be the limiting factor. These resonances limit the phase advance of each basic cell to within $\pi/2$ to $\pi/3$, and thus the momentum acceptance is highly constrained.
4. I also find that the emittance growth factor for quadrupole and skew-quadrupole errors obeys a simple scaling law:

$$\mathrm{EGF} = \exp\left[\frac{\lambda 2\pi g^2}{d\nu / dn}\right]$$



# Electron Mode for Proton Acceleration
A.G.Ruggiero(BNL)

## Electron Model for Proton FFAG Accelerator

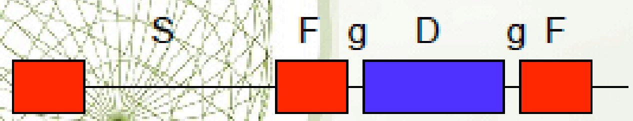



*Table1. Lattice Parameters of Electron Model*

| | |
|---|---|
| Circumference | 9.05484 m |
| Period Length | 0.377286 m |
| No. of Periods | 24 |
| F: Length | 4.375 cm |
| Field | -38.717 G |
| Gradient | 3,739 G/m |
| D: Length | 8.75 cm |
| Field | 90.586 G |
| Gradient | -3,275 G/m |
| Drifts: S (half), cm | 8.239 |
| g (full), cm | 1.875 |
| Phase Advance, H/V | 0.32589 / 0.28593 |
| Betatron Tune, H/V | 7.82122 / 6.86230 |
| Transition Energy, $\gamma_T$ | 16.914 i |
| Chromaticity, H/V | -0.8274 / -1.8493 |

*Table 2. Acceleration Parameters of Electron Model*

| | Injection | Extraction |
|---|---|---|
| Kinetic Energy, keV | 217.85 | 816.93 |
| Momentum, keV/c | 519.73 | 1,225.66 |
| β | 0.71306 | 0.92300 |
| Revol. Freq., MHz | 2.3618 | 3.0552 |
| Revol. Period, μs | 0.4234 | 0.3273 |
| Harmonic Number | | 3 |
| RF Frequency, MHz | 7.085 | 9.166 |
| Bunch Area (full), eV-s | | 0.40 |
| Peak RF Voltage, kVolt | | 5.824 |
| Energy Gain, keV/turn | | 2.427 |
| No. of Cavities | | 1 |
| No. Electrons / Cycle | | $5.446 \times 10^{10}$ |
| Circul. Current, mA | 20.59 | 26.659 |
| Beam RF Power, W | 50.04 | 65.13 |
| Space-Charge Δν | 0.50 | 0.16 |
| Full Emittance, norm. | 100 π mm-mrad | |
| Repetition Rate, Hz | 2.5 | |
| Injection Period | 0.1122 ms (255 turns) | |
| Acceleration Period | 0.7854 ms (2,200 turns) | |
| Total Period | 0.8976 ms | |

# Conclusion

- New schemes come to be reality!
  - HNJ acceleration
    - harmonic number jump acceleration
  - ERIT new protondriver w. internal target
    - Emittance/Energy recovery internal target
  - NFFAGI lattice
    - non-isochronous, zero-chromatic non-scaling & nonlinear lattice

We will hear more at next workshop in Osaka!