Space charge study in ERIT (version 0.32)

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Goals (tentative)

- Is bunch charge limit the same as one in a synchrotron?
    - Is transverse tune spread of 0.25 (for example) achievable?
    - Resonance lines are denser with stronger nonlinearity.
    - Can be suffered more from image charge and current.
- Does transverse painting work?
    - Does it create desirable distribution and reduce peak density?
    - (Nonlinear) coupling in two transverse planes is stronger.
- Does large aperture in horizontal help?
    - Can we keep anisotropic emittance?

Steps

- Back of the envelope calculation
- Modelling with codes
- Beam experiments
- Hardware developments

Back of the envelope calculation (0)

- Basic beam parameters

  T = 11 MeV (E = 949.272 MeV)

  P = 144.094 MeV/c

  γ = 1.011724

  β = 0.151794

  ε_{rms} = 8 π mm mrad (unnormalized, rms)

  $\varepsilon_{95\%}$ = 48 (=6 x 8) π mm mrad (unnormalized, 95%)

  dT/T = 0.1% (rms)

  (dp/p = 0.05% (rms))

Back of the envelope calculation (1)

- Tune shift (for uniform beam) $$\Delta Q = -\frac{r_p n_t}{2\pi\varepsilon\beta^2\gamma^3}\frac{1}{B_f}$$

$\varepsilon_{100\%}$ = 100 π mm mrad (unnormalized, 100%)

$B_f = 0.25$

$n_t = 6 \times 10^{11}$

gives $\Delta Q = -0.25$

- Number of particles $$n_t = 2\pi R \cdot TN \cdot \frac{I}{e\beta c}$$

R = 2.35 m

TN = 59 (or 19 micro s)

I = 5 mA

gives $n_t = 6 \times 10^{11}$

Back of the envelope calculation (2)

- Bucket height

$$B_h = 2\sqrt{\frac{eV}{2\pi\beta^2 Eh|\eta|}}$$

V = 0.225 MV

E = 11 + 938 MeV

h = 6

\eta = \alpha_t – 1/gamma^2 = -0.633

gives B_h (=dp/p) = 4.15 x 10^{-2}

- Synchrotron tune

$$Q_s = \sqrt{\frac{heV|\eta|}{2\pi\beta^2 E}}$$

gives Q_s = 7.88 x 10^{-2} (or 13 turns)

Back of the envelope calculation (3)

- Longitudinal space charge

$$F_{sc}/e = -\frac{eg_0}{4\pi\varepsilon_0\gamma^2}\frac{\partial\lambda}{\partial s}$$

$$g_0 = 1 + 2\log\frac{d}{a}, \lambda = -k_2 s^2 + k_0$$

k_0 = 7.317 x 10^{11}

k_2 = 1.935 x 10^{12}

Sqrt[k_0/k_2] = \lambda_rf/4 and n_t = 6 x 10^{11}

g_0 = 2

gives (F_{sc}/e)/s = 1.1 x 10^4

- rf voltage

$$F_{rf}/e = V\sin\left(2\pi s/\lambda_{rf}\right) = \frac{2\pi Vs}{\lambda_{rf}}$$

V = 0.225 MV

\lambda_rf = 2πR/h = 2.461 m

gives (F_{rf}/e)/s = 5.7 x 10^5

Back of the envelope calculation (4)

- Energy loss by foil scattering

dE = 0.760 kV per turn (Okabe at FFAG10)

\phi_s = asin(0.760/225) = 0.19 degree (negligible)

However, with coasting beam operation

DE = dE x TN = 0.760 kV x 1000 turns (for example) = 0.76 MeV

gives DE/T = 6.9×10^{-2}

- Overlapping of linac micro structure

$$dt = \eta \frac{dp}{p} t_{rev}$$

f_Linac, rf = 425 MHz (Okabe at FFAG10)

f_rev = 3.02 MHz (f_ERIT, rf = 18.1 MHz)

gives f_Linac, rf/f_ref = 141

n_debunch = (t_rf/t_rev)/(\eta x dp/p) = 1/(141 x 0.633 x 0.0005) = 22 turns

Modelling with codes (1)

- Simulation of capture in bucket (1D only)

  Assuming no chopper, estimate the number of particles captured in a rf bucket.

  Estimate bunching factor.

  With foil scattering, estimate longitudinal emittance.

Modelling with codes (2)

- Simulation of foil scattering

  Without space charge effects, estimate emittance evolution by foil scattering.

  (I assume that the previous simulation does not have multi-turn injection process.)

  Simulate (or superimpose) multi-turn injection process.

  Simulate off-axis injection process.

Modelling with codes (3)

- Simulation of transverse emittance evolution with space charge

  Without foil scattering effects, estimate emittance evolution by space charge code such as Simpsons.

  Lattice can be modelled as an ordinary synchrotron lattice with many multipoles.

  Scan 2D tune space.

  Introduce fringe field and/or measured COD.

  Compare emittance growth due to space charge and due to foil scattering.

Beam experiment (0.1)

- Beam emittace (size) measurement vs. turn number

  Fix collimator aperture slightly larger than the linac beam.

  Identify time (turn) when beam loss starts appearing.

  Enlarge collimator aperture a little larger and identify time (turn) when beam loss starts appearing.

  Repeat the above process and plot collimator aperture (on y-axis) vs. time (turn) when beam loss starts (on x-axis).

Beam experiment (0.2)

- Orbit matching

  Repeat the beam emittance (size) measurement with slightly different initial injection orbit.

  When a beam is injection on axis, growth should be minimum.

Beam experiment (0.3)

- Foil position

  Repeat the beam emittance (size) measurement with different foil position.

  Can we reduce the hitting probability?

  Can we optimize the foil position such that large amplitude particle will escape from foil scattering but still in the aperture?

Beam experiment (1.1)

- Without rf
- Beam emittace (size) increase by foil scattering.

  Inject small number of particles on axis (less than ~100 turns, but enough to do emittance measurement on the previous).

  Measure beam emittance (size) vs. time (turn).

  This process should be independent of beam intensity so that we can use the result to estimate emittance growth purely from scattering when more number of particles are injected.

Beam experiment (1.2)

- Without rf
- Beam emittace (size) increase by foil scattering and space charge.

Inject large number of particles on axis (~240 turns or more, which should make tune shift of ~-0.25).

Measure beam emittance (size) vs. time (turn).

Can we identify emittance growth on top of foil scattering?

Beam experiment (1.3)

- Without rf
- Same as (1.1) to (1.2), but inject off axis.

Growth rate dε/ε by scattering becomes relatively smaller.

However, need more number of particles to make the same space charge tune shift.

Is this easier to separate emittance growth by foil scattering and space charge?

Beam experiment (2)

- With rf
- Basically the same procedure of (1.1) to (1.3)

However, physics is different. Not quantitative difference due to bunching factor, but qualitative difference due to synchrotron oscillations, resonance crossing, etc.

Monitor bunch profile.

Beam experiment (3)

- After establish the way to observe space charge effects, explore parameter space.

  rf voltage

  rf gymnastics around injection

  2D scan in tune space.

  With and without COD correction.

  Start from anisotropic emittance.

  etc.

Hardware developments

- Bump magnets
  - Single or pi-bump?
- Beam position
  - BPM
- Beam profile
  - Scraper
  - Flying wire
  - Ionization profile monitor