Report of Working Group I

Convenors: Koscielniak & Machida

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I Thanks to our hosts

II Much of the "to do" list from April '04 workshop has been accomplished (between or during this w/s)

- public relations & community recognition effort continues with AIP proceedings for this workshop
- tracking studies of resonance crossing
  ⇒ tolerances on alignment + gradient errors
- improved cost model for μ FFAG including externalities such as the experiment (detector)
- finding a home (maybe?) for e-model
- diagnostic strategy for e-model.

III Exciting development
isochronous semi-scaling FFAG
$\gamma = \gamma_t$ Rees
$\gamma > \gamma_t$ Schönauer

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Isochronous semi-scaling FFAG   # free params > # tuns

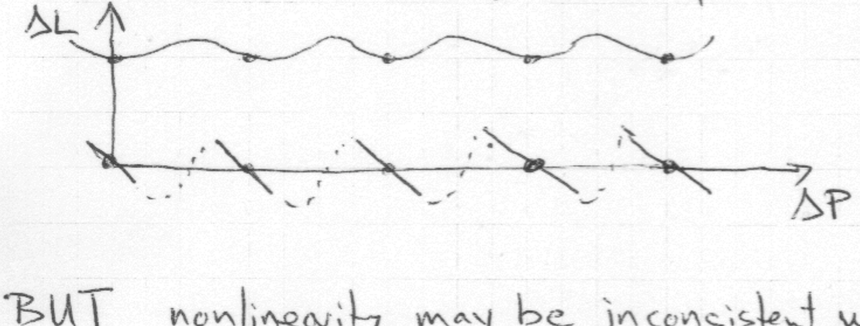
Rees Cell has 5 magnets. Ability to adjust $B_0 + B_1$ (field, gradient) for each orbit leads to nonlinear magnets $\gamma = \gamma_t$
Compared to Carol's 1.2km 3-element lattice, new approach allows longer straights, fewer cells.
$\Delta T / T_0 \sim 10^{-5}$ ←

Schönauer has simplified lattice somewhat, $\gamma > \gamma_t$.
particularly geometry of elements

Rees m/c ⇒ on-crest acceln, resistive loading of cavity.
Schönauer ⇒ off-crest acceln with synchrotron style bucket

[Rees m/c holds promise of near perfect isochronism + zero chromaticity.]

Should be pursued.
Need to identify functional form of residual ΔT
– understand limits to longitudinal dynamics.



Warrior $\gamma = \gamma_t$

Hirosato $\gamma > \gamma_t$

BUT nonlinearity may be inconsistent with huge $\underline{\perp}$ acceptance
Need tracking studies to identify influence of nonlinear resonances (Meot, etc)

③

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VARIABLE-TUNE LINEAR-FIELD FFAG

Non-scaling μ FFAG (S. Berg)

Have an improved cost model for accelerator components.
— e.g. includes fixed-costs of magnet fabrication.

Market economy approach to decision making — Adam Smith to Milton Friedman.
However, like trans-national corporations,
we have been externalising costs. and passing them on to the experiment.
Cost model now includes marginal increase of detector cost with respect to μ decay loss.
Cost function nolonger flat, and small rings with strong bend fields are now favoured. (just as they were a year ago!)

Cost model has still room for improvement.

- include measuring of operating costs
- internalize cost to μ-cooling of FFAG aperture selection.
- find a cost-function to inform our choice of

$$(a, b) = \left[\frac{\delta E}{\Delta E} \frac{1}{\omega \Delta T} , \frac{\delta T_2}{\delta T_1} \right]$$

i.e. quantify the cost of non-linear emittance distortion.
Some aspects of this issue quantified by Koscielniak
(dwell time, acceleration efficiency, time dispersion).

τ $\langle \cos x \rangle$ $\frac{1}{2!} \frac{\partial^2 \tau}{\partial H^2}$

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Election Model –.

i) Most significant development is enthusiasm of Daresbury and RAL to consider hosting ~~the~~ e-model. Possibility to realise hard work and creativity of last 4 years is exciting and rewarding.

Under ASTEC initiative an 8-35 MeV ~~Electr~~ electron energy recovery linac, with variety of time structure, is constructed in next two years.

ii) Issue is choice of RF
e-model : S-band (3 GHz) recuperate SRS equipment?
linac : L-band (1.3 GHz)

single bunch operation decouples RF choice between machines and will ease kicker rise/fall requirements also.

Cost/opinions of Kazushi Hanakawa

3.3 GHz	single klystron, waveguide distribution	good option
1.3 GHz	ditto	not ruled out
0.85 GHz	30 IOT + low-level RF	rejected

[Three ugly sisters, no Cinderella here]

~~New~~ requirements to feed into e-model
range of $a = [0, \frac{1}{4}]$ subspace of $[0, \infty]$
New ⇒ of $b = [0, \frac{1}{2}]$ $[0, 1]$
⇒ tunability of RF or ring circumference

Electron Model Continued.

iii) Tracking Studies of Resonance Crossing.

[Also nice experimental studies @ PoP & HIMAC by Aiba]

The studies give confidence that integer + $\frac{1}{2}$ integer resonances may be crossed with negligible $\frac{1}{4}$ emittance blow up. Keil reported study at April workshop (his own lattice?) Machida presented studies using SIMPSONS here with Trbojevic + Courant lattice.

Tolerances are demanding but achievable:

alignment	<30 μm rms, gaussian (Keil)		5 turns limit
	<50 μm 100%, uniform (Machida)		
gradient error	<0.5%	0.1% achieved JPARC	

Machida also reported synchro-betatron type effect due to m/c errors changes of pathlength ⇒ reduced asychronism

iv) Practicalities of alignment, etc.

a) single concrete slab for entire machine

b) two cells per girder - alignment within girder 10 μm (use laser tracker and piezo actuators)

c) alignment between girders using central laser tracker <50 μm

d) support vacuum chamber independently of magnets

e) laser tracker needs clear line of sight unobstructed by λ guides

To achieve better accuracy use beam-based alignment

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Electron Model continued

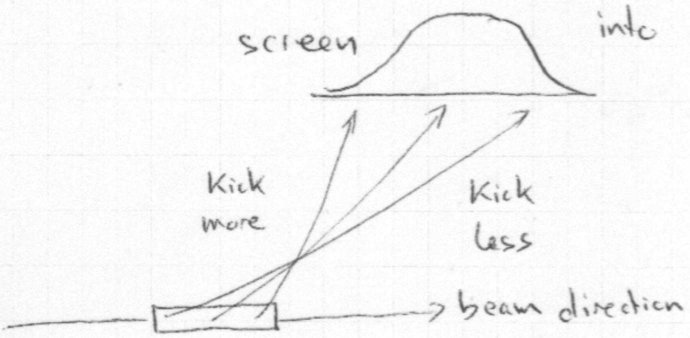
v) Diagnostics

- closed orbit BPMs : 2 per plane per cell.
  with 3cm aperture , 3 μm resolution possible
  BUT needs extreme care over low noise electronics.

  BPMs used also to infer beam momentum. [No spectrometer]
  (disentangle ⊥ & ∥ ?)

- ⊥ emittance measurement
  No option but to kick out e to emittance rig
  — pepper-pot plate, fluorescent screen + CCD camera.
  [whole bunch gets same kick]

- longitudinal profile
  time structure is beyond reach of wall-current monitor.
  Use transverse-deflecting cavity and fluorescent screen
  Kick varies along bunch ⟹ time dependence converted into position dependence



BUT centre line from which we kick changes with momentum

- exploration of longitudinal phase-space vastly facilitated by continuous energy variability of linac.
  — may also help study resonance crossing.

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Electron Model Continued.

vi) SPECULATION

One ~~practic~~ key purpose of the model is to benchmark the scaling laws for resonance crossing.

e-model should demonstrate x-ing speeds at least as slow as μ FFAG — without need to install LF cavity.

Suggestion (Koscielniak) that crude measure of speed is

$$s \equiv \frac{1}{N_c N_T} = \frac{\delta P}{\Delta P} \langle \cos x \rangle = a(\omega \Delta T)$$

Criterion for e-model $\quad s_e \leq s_\mu$?

Keil's EPAC04 lattice is a move in correct direction $N_c \uparrow$, $L_o \downarrow$

Is it good enough?

vii) "To do"

- injection & extraction – details & concepts!
- costings

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A crossing speed argument

relevant parameter is $\dfrac{\dot{\nu}}{\nu} = \dfrac{\dot{\phi}}{\phi}$ ν = tune
ϕ = cell phase advance

machine with large # cells has larger $\Delta\nu$, but time to cross is longer also because also proportional to N_{cell}.

To lowest order, relation between ϕ and quad strength

$A \equiv \dfrac{B l c}{P}$ B = field, p = momentum, l = length

$$A^2 \simeq \frac{3(1-\cos\phi)}{L_0 (l_d + l_f + 3l_0)}$$ L_0 = cell length, l_0 = drift length

$$\therefore \frac{(1-\cos\phi) \text{ @ injection}}{(1-\cos\phi) \text{ @ extraction}} = \left(\frac{\hat{P}}{\check{P}}\right)^2$$

Hence if ratio of injection to extraction momenta are equal between two machines, then crossing speed proportional $\dfrac{1}{N_c N_t}$
#cells $\rightarrow N_c$, $N_t \leftarrow$ # turns

BUT $N_c N_T \, \delta P \langle \cos x \rangle = \Delta P$
δP = per cell impulse; ΔP = machine range

Hence crossing speed $\propto \dfrac{\delta P \langle \cos x \rangle}{\Delta P}$ reducing range alone does not reduce xing speed

Scott's param

Now $\dfrac{\delta P}{\Delta P} = W(\omega \Delta T) \geqslant \dfrac{1}{24} \omega \Delta T$

So lower frequency ω, or ToF range ΔT to reduce crossing speed.

For optimised FFAG lattice

$$\Delta T = \frac{3}{4} \frac{(\hat{p} - \check{p})^2 \; \Theta^2}{(\check{p})^2 \; (1 - \cos\phi)} T_0 \qquad (1)$$

Θ = bend angle of half cell = π / N_c
T_0 = ToF across cell at reference energy

Now for gutter acceleration $\frac{\delta P}{\Delta P} = w(\omega \Delta T) > \frac{1}{24} \omega \Delta T$

All other params being equal, we are interested to scale ωT_0 between μ and e machines.

$$\omega T_0 = \frac{\omega}{c} \left[L_{magnet} + L_{RF} \right] \qquad L = \text{"length"}$$

$$L_{RF} \simeq \frac{3}{4} \lambda = \frac{3}{2} \frac{c}{\omega} \pi$$

$$L_{magnet} \simeq 3 \frac{\bar{p}}{eB} \frac{\pi}{N_c}$$

B = field, e = charge
$\bar{p} = (\hat{p} + \check{p})/2$

$$\omega T_0 \simeq \frac{\omega}{c} \frac{3 \bar{p} \pi}{e B N_c} + \frac{3\pi}{2}$$

Now for the scalings...

[Ideally ratio L_{mag}/L_{RF} should be same between machines] not too important

$\frac{\bar{p}(\mu)}{\bar{p}(e)} = 10^3$ which gives mm magnet lengths

$\therefore$ back off the field, B 4 Tesla $\to$ 0.2 Tesla

$\Rightarrow$ magnet length $\simeq$ 10cm for combined function "D"

$\frac{L_{mag}(\mu)}{L_{mag}(e)} = \frac{10^3}{20} = 50$ and wavelength λ to be scaled in same way.

$\frac{RF(e)}{RF(\mu)} = 50 \quad \therefore \quad RF(e) = 10\,GHz$

$RF(\mu) = 0.2\,GHz$

BUT the structure is awfully small (fiddly)

Scott reduced frequency by factor 3. $RF \Rightarrow 3\,GHz$.

$$\omega T_0 \simeq \frac{3\pi}{2} + \frac{\omega}{c}\frac{3}{e}\frac{\langle p \rangle \Theta}{B} \qquad \overset{\mu}{\omega} \Rightarrow \overset{e}{\frac{50\omega}{3}} \qquad \overset{\mu}{\frac{\langle p\rangle}{B}} \Rightarrow \overset{e}{\frac{1}{50}\frac{\langle p\rangle}{B}}$$

$$\Rightarrow \frac{3\pi}{2} + \frac{\omega}{c}\frac{1}{e}\frac{\langle p \rangle \Theta}{B} \qquad \Theta \Rightarrow 3\Theta, \quad N_{cell} \Rightarrow \frac{N_{cell}}{3}$$

BUT look at formula ① and Θ^2 term

This electron model is a <u>harder</u> machine than 10–20 GeV μ despite fact that frequency is artificially low.

In its present form, x-ing speed is faster!

To make it lower, either $\omega \downarrow$ or $(N_c \uparrow)$ (1.3 GHz?) → smaller frequency sweep

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<u>Note</u> The demonstration model will test

i) gutter acceleration ii) resonance crossing

BUT it cannot do these simultaneously $\Big\}\to$ phase II LF

except at high crossing speed.

If acceleration is in buckets  or $\delta T_2 = 0$

still cannot get slow x-ing speed.

e.g. $b=0$ range $\propto a^{-1/3}$ $\tau \propto 1/a^{2/3}$

x-ing speed $\propto \frac{\text{range}}{\text{dwell}} = a = \frac{\delta P}{\Delta P}\frac{1}{\omega \Delta T}$

A step backward, but its important to understand scenarios

- "as is" e-model $\Big<$ x-ing speed faster than μ / future LF system to lower speed

- revise e-model $N_{cell} \uparrow$ and/or $\omega \downarrow$

$\Rightarrow$ • x-ing speed same as 10–20 GeV μ

  - still need LF system to get to low x-ing speeds

- Both cases flat-topping could, may be, halve x-ing speed.

<u>What is scaling law</u>?

$$\frac{1}{a}\frac{\delta P}{\Delta P} = \omega \Delta T = \frac{3\,\Delta P^2 \quad \Theta^2}{4\,\left(\frac{v}{p}\right)^2 (1-\cos\phi)}\left[\frac{\omega\, 3\langle p\rangle\,\Theta}{c\,e\,B} + \frac{3\pi}{2}\right]$$

Want $\omega \Delta T$ small $\therefore$ prefer NOT $\propto \Theta^3 \Rightarrow \omega \downarrow$

Could be argument for 1.3 GHz?