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Status of FFAG codes benchmarking

Shinji Machida

FFAG workshop, 6-9 September 2016

Set up a plan at BNL in 2014

KURRI FFAG Simulation Plan – second draft

S. L. Sheehy 27/9/14
A. Adelmann 28/9/14
A. Adelmann, F. Méot, M. Haj Tahar & N. Tsoupas 29/9/14
S. L. Sheehy, S. Machida, 01/10/2014
S. Machida, 01/10/14
S. Machida, 27/10/14
S. L. Sheehy 3/12/14

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First report at IPAC 2015

Proceedings of IPAC2015, Richmond, VA, USA MOPJE077

PROGRESS ON SIMULATION OF FIXED FIELD ALTERNATING GRADIENT ACCELERATORS

S. L. Sheehy*, JAI/Oxford and STFC/ASTeC/RAL, UK
D. J. Kelliher, S. Machida, C. R. Prior, C. Rogers, STFC/ASTeC/RAL, UK
M. Haj Tahar, F. Meot, BNL, USA
Y. Ishi, T. Uesugi, Y. Kuriyama, M. Sakamoto, Y. Mori, KURRI, Japan
A. Adelmann, PSI, Switzerland

"based on KURRI 150 MeV FFAG model"

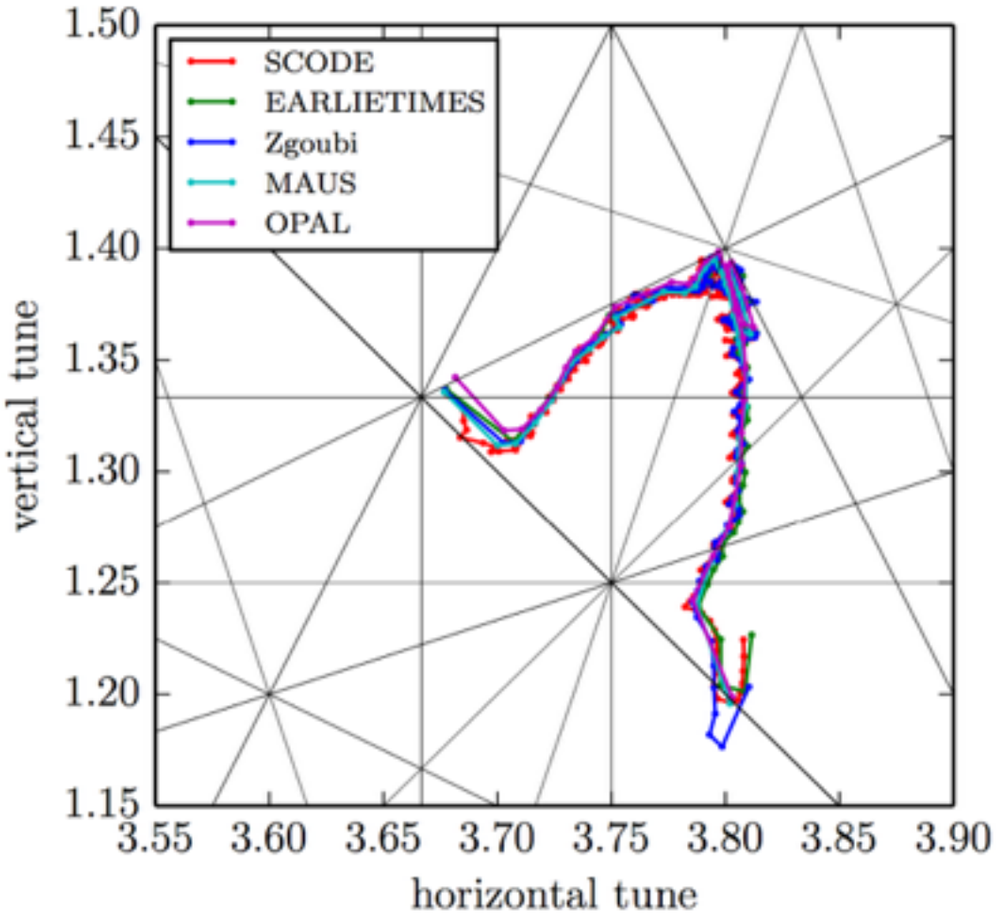
codes participated

OPAL, ZGOUBI, SCODE, MAUS, EARLIETIMES

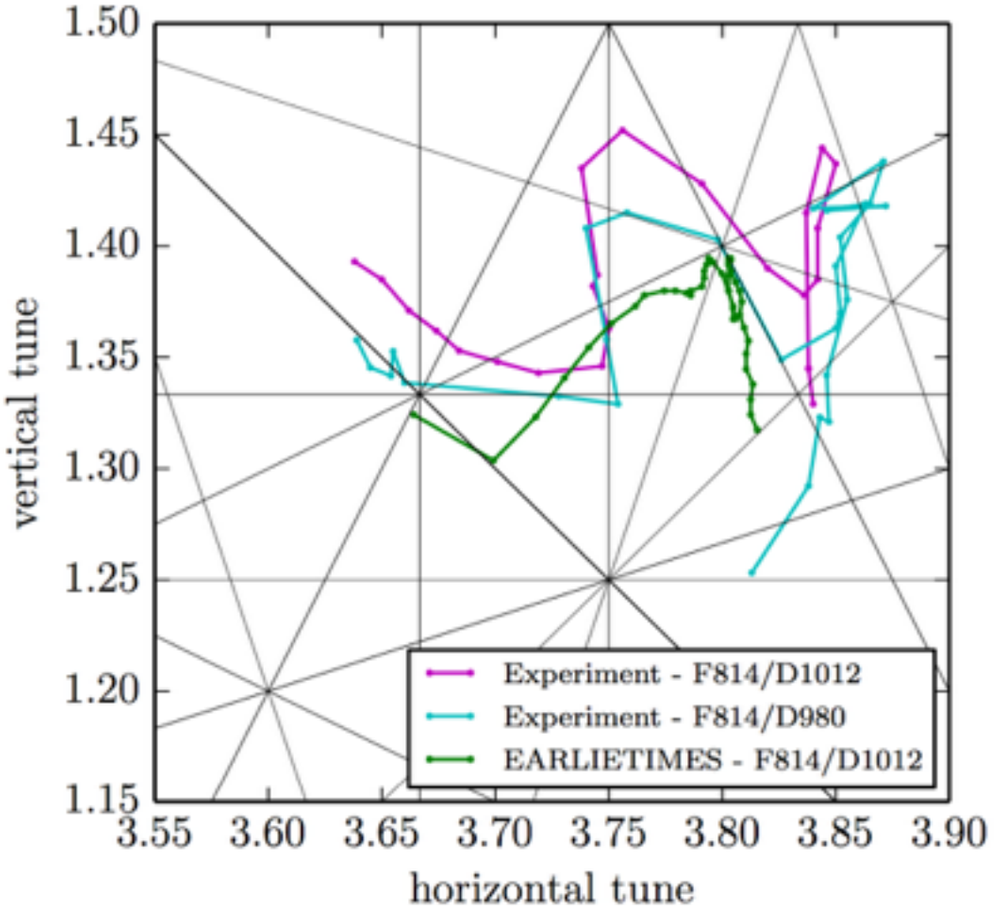
Transverse tune

Findings (1)

tune with 3D TOSCA field map



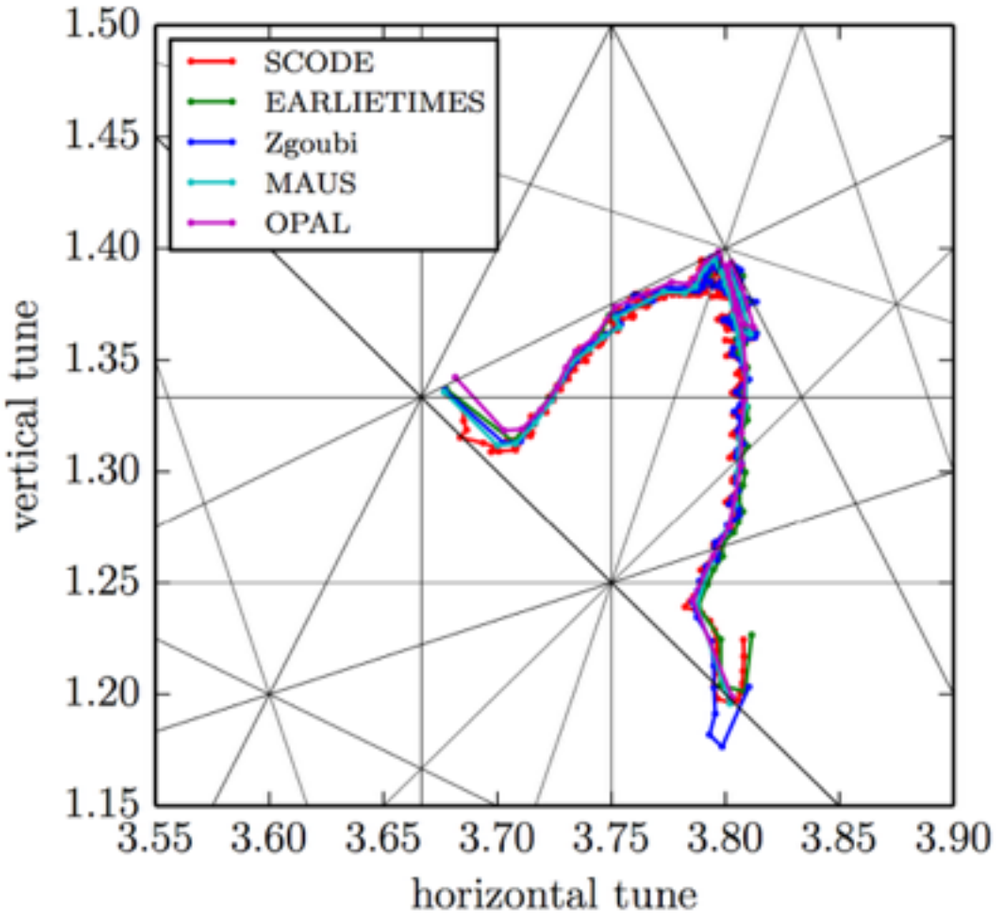
codes vs codes



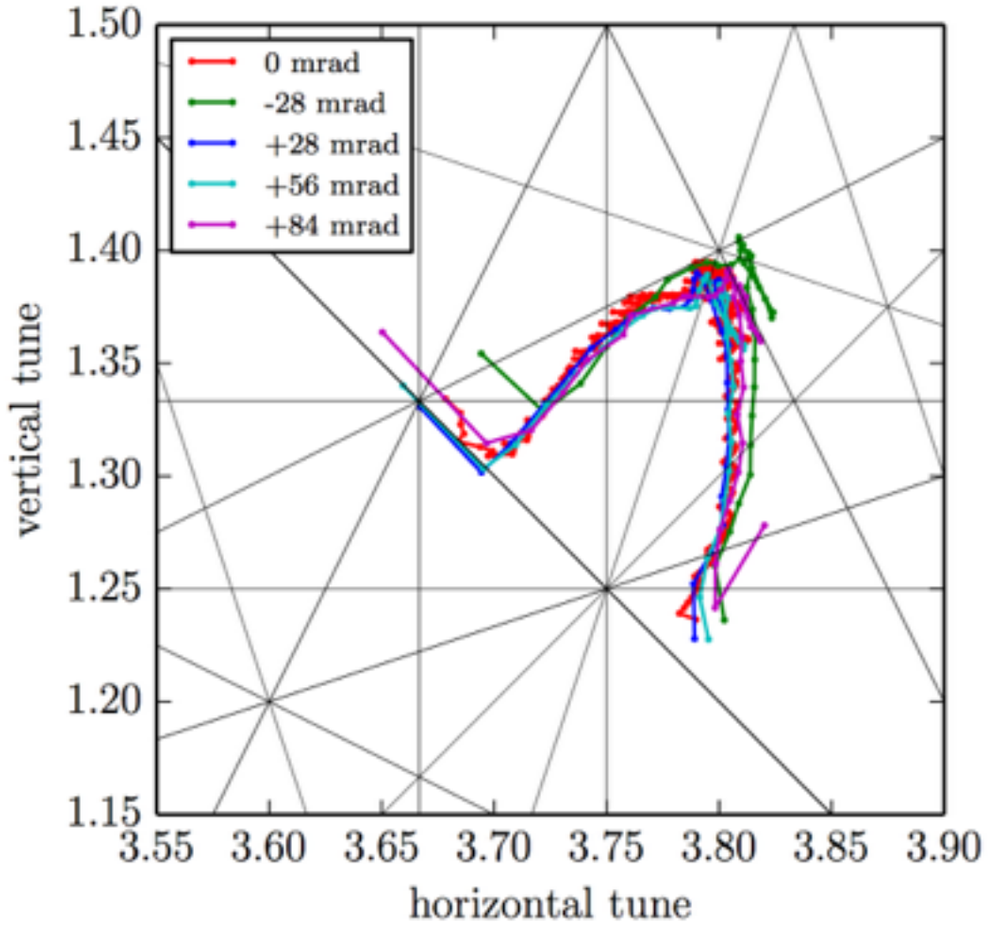
codes vs measurement

- All codes give the similar results except at the start and the end.
- However, measurement results do not agree with the codes!

Findings (2)
effect of COD



codes vs codes



with COD

- Realistic COD (~ cm) does not change the tune foot print.

Study at Kyushu FFAG (1)

effect of "patch"

https://www.cabas.kyushu-u.ac.jp/indico/event/0/contribution/2/material/slides/0.pdf

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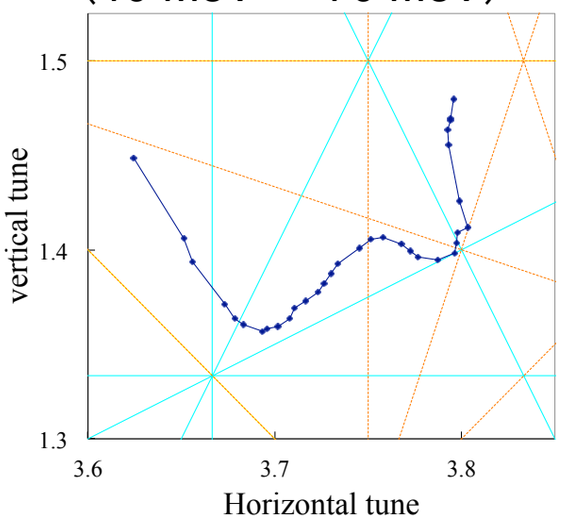
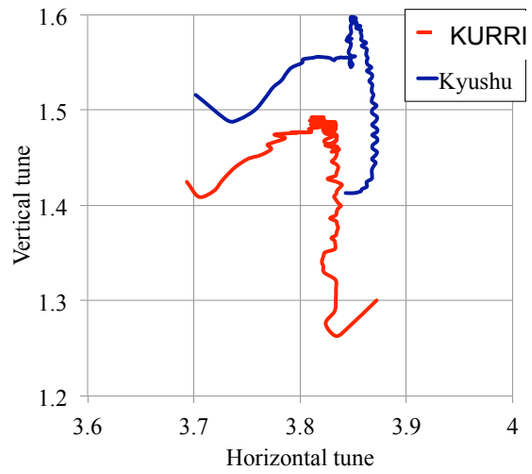
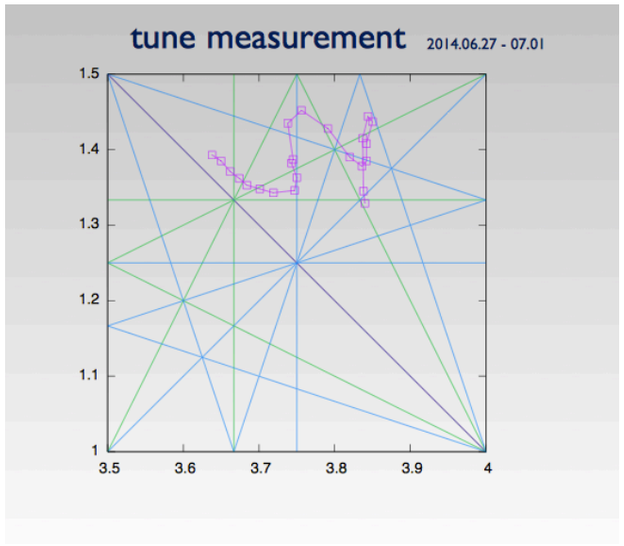
Measured tune at KEK
（10 MeV ～ 70 MeV）



tracking simulation



Measured tune at KURRI *



- Movement of tune is different at low magnetic field.

⇒ Patch？

* Y.Ishi FFAG14 BNL NY sep 22 2014
https://indico.bnl.gov/getFile.py/access?contribId=115&sessionId=18&resId=0&materialId=slides&confId=686

Study at Kyushu FFAG (2)

effect of "patch"

https://www.cabas.kyushu-u.ac.jp/indico/event/0/contribution/2/material/slides/0.pdf

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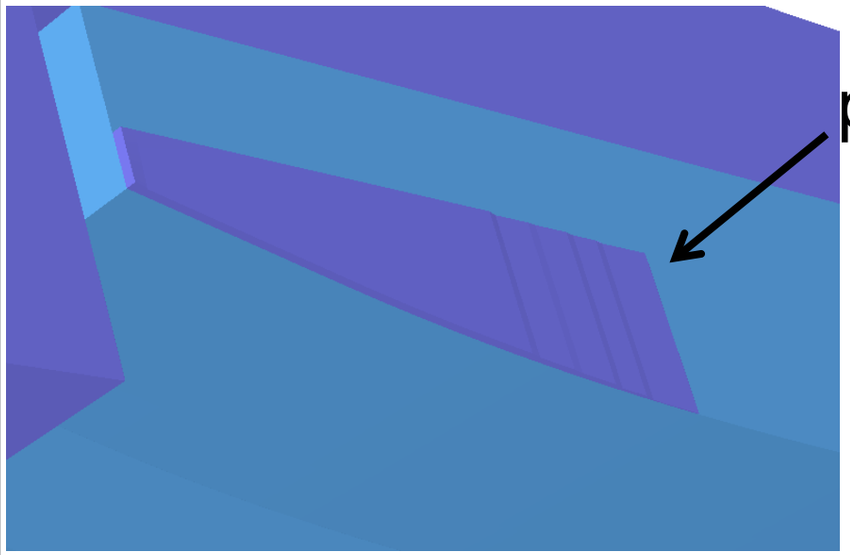
Vertical tune control

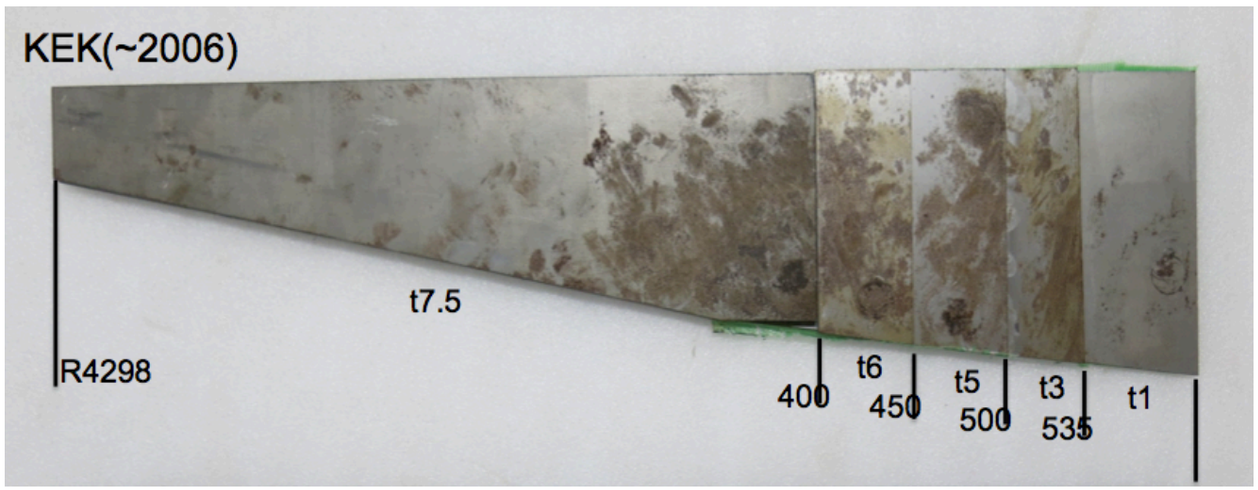


patch（additional magnetic pole）

thickness：7.5 mm ~ 1mm

radius：429.8 cm~ 489.8 cm

kinetic energy：
10 MeV ~ 57MeV



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Study at Kyushu FFAG (3)
effect of "patch"

https://www.cabas.kyushu-u.ac.jp/indico/event/0/contribution/2/material/slides/0.pdf

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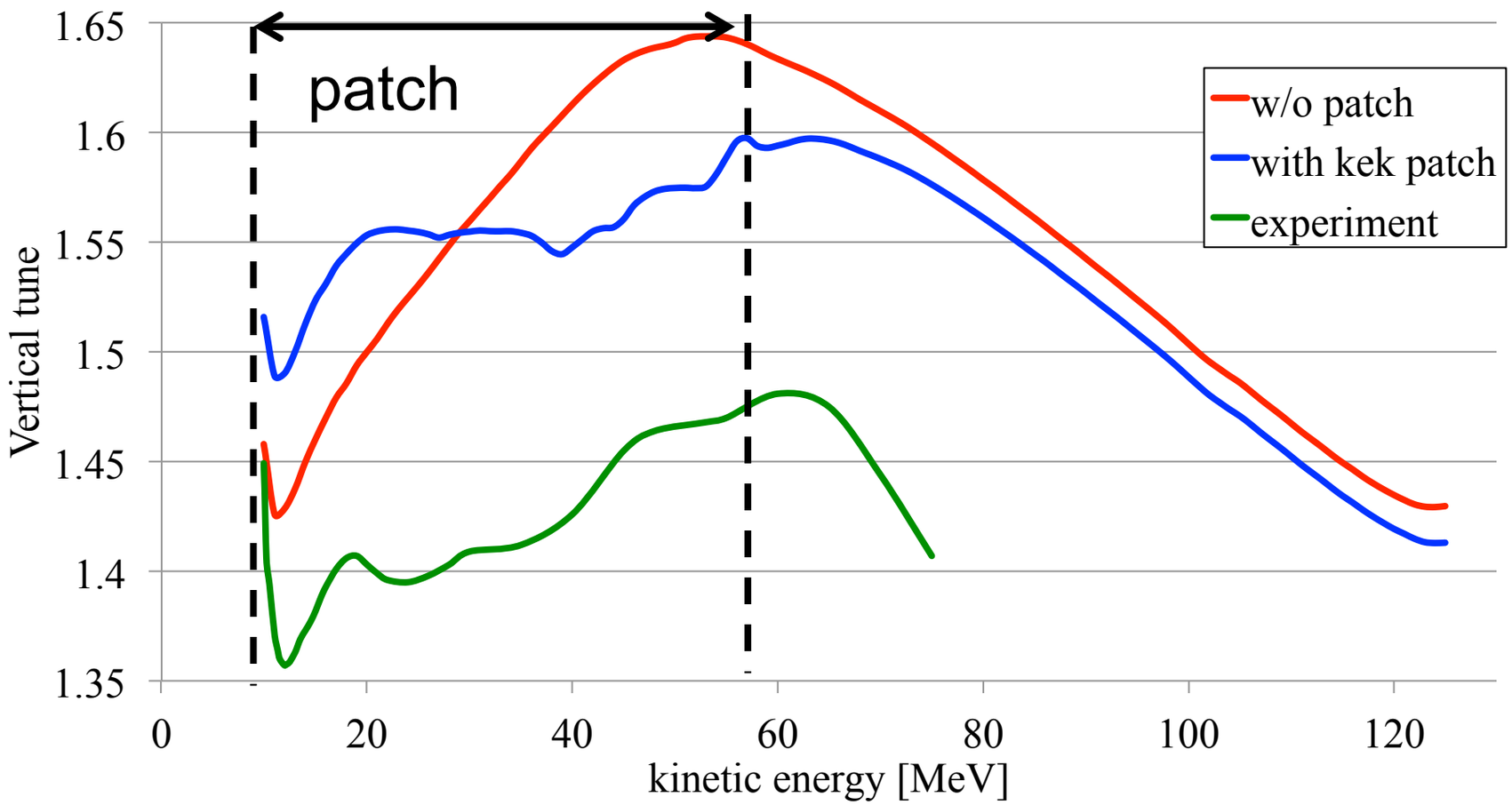
Vertical tune control



$$\Delta\nu_V = 0.2176 \Longrightarrow \Delta\nu_V = 0.1083$$

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Transverse tune
summary

- 3D mesh has to be small enough (Motohashi at FFAG2015).
- Details of the magnet like a “patch” is important for benchmarking.

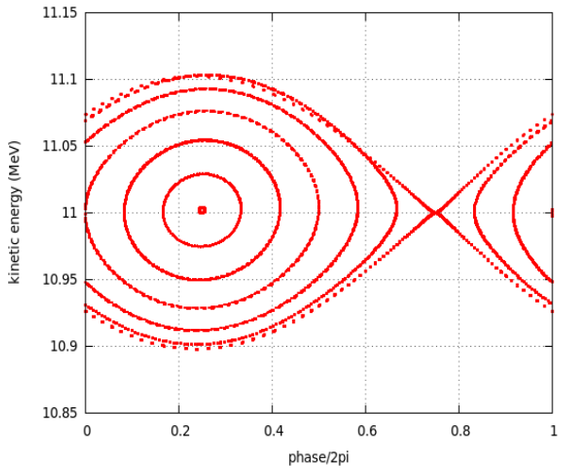
- Calculation of new TOSCA 3D data was proposed.
- Time to consider it more seriously?

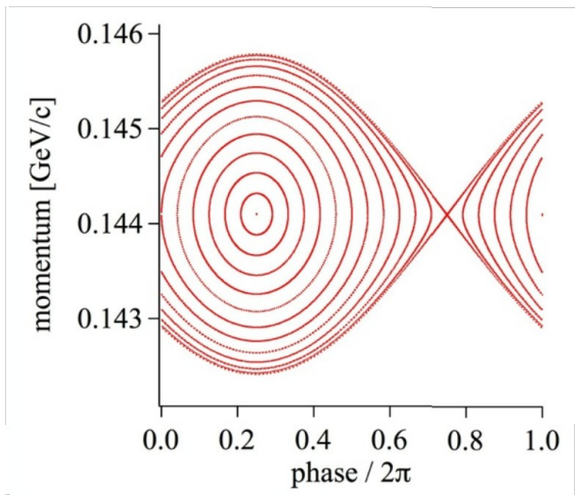
Longitudinal motion

Findings (1)
tune with 3D TOSCA field map

Longitudinal phase space without RF

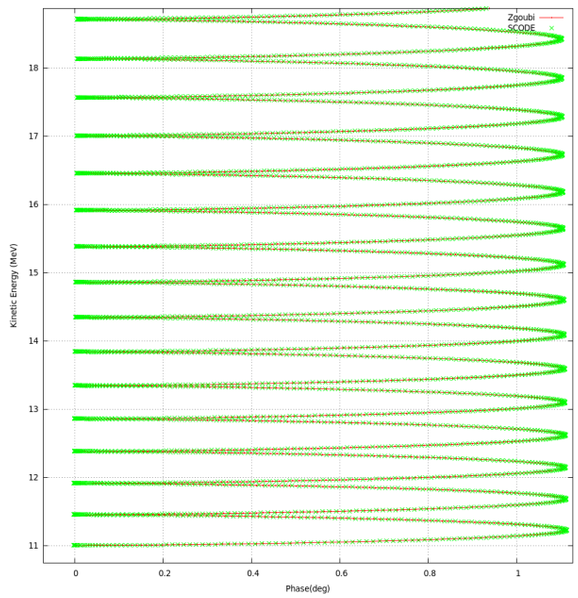
- Zgoubi

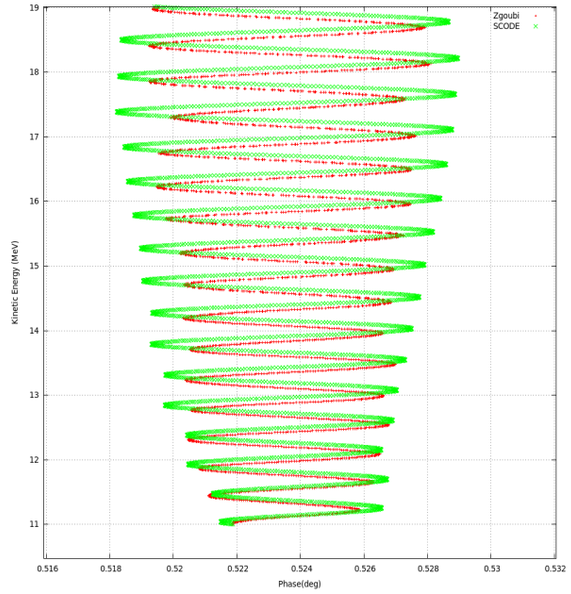




- Scode

Longitudinal phase space with RF





- RF law with variable k.

- Good agreement between ZGOUBI and SCODE with and without acceleration after some debugging.

Emittance evolution

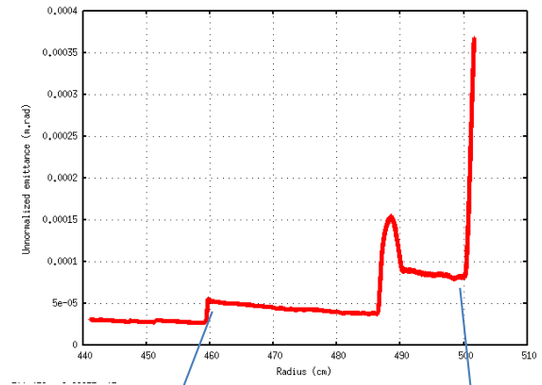
Emittance evolution with 2D and 3D field data

ZGOUBI

2D vs 3D field map

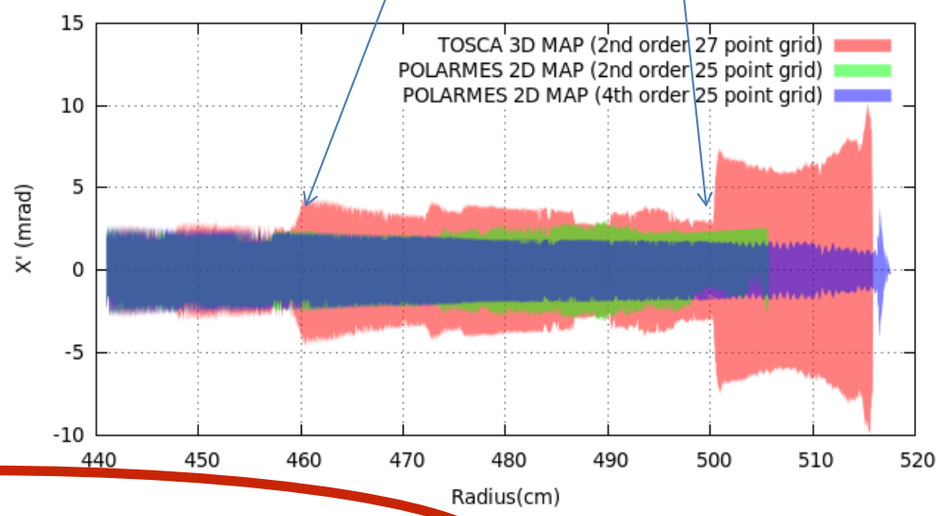
Malek's findings:

The horizontal emittance increase at certain locations is observed from single particle tracking using the 3D TOSCA field map.



Pattern-filled curves

Single particle acceleration with 3D and 2D field maps and using different interpolation methods.

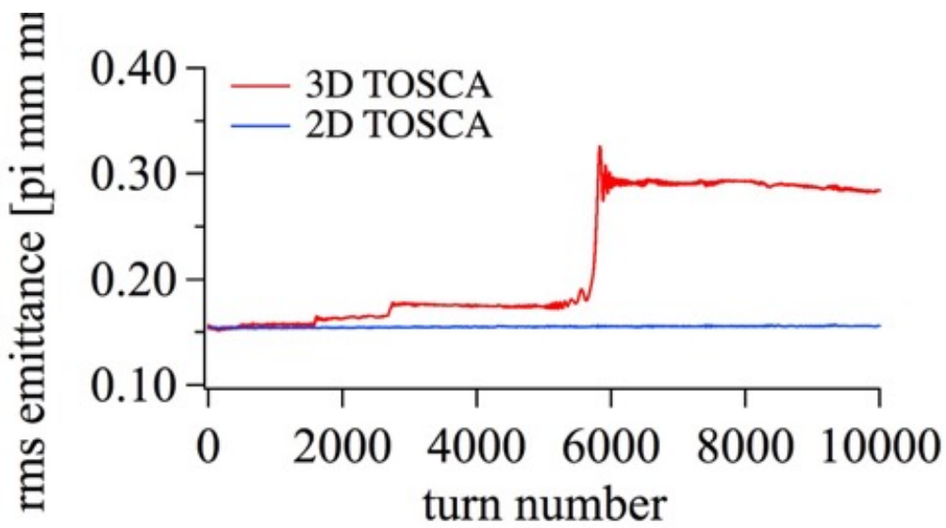


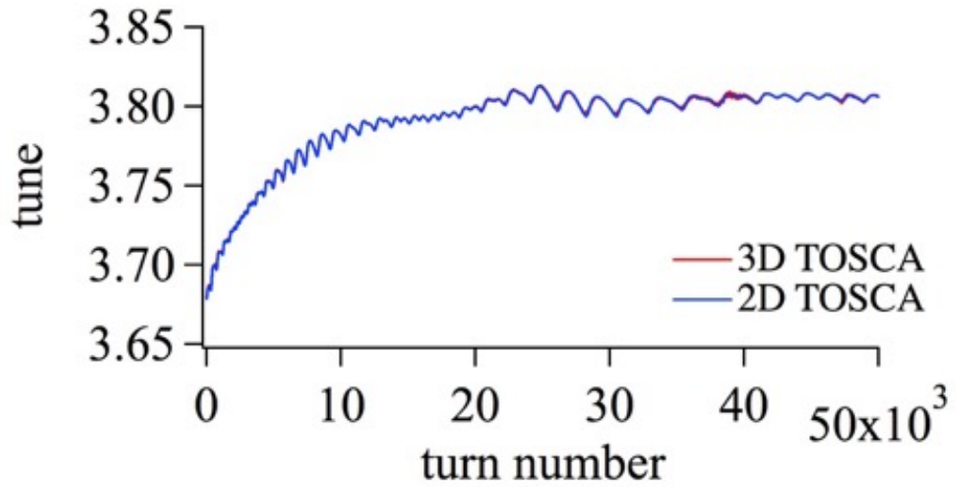
The problem seems to disappear with the 2D field map

Emittance evolution with 2D and 3D field data

SCODE

Confirmed by s-code





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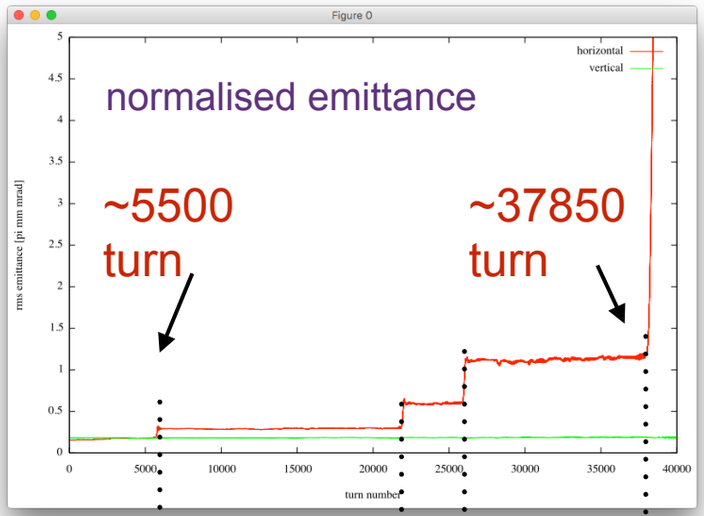
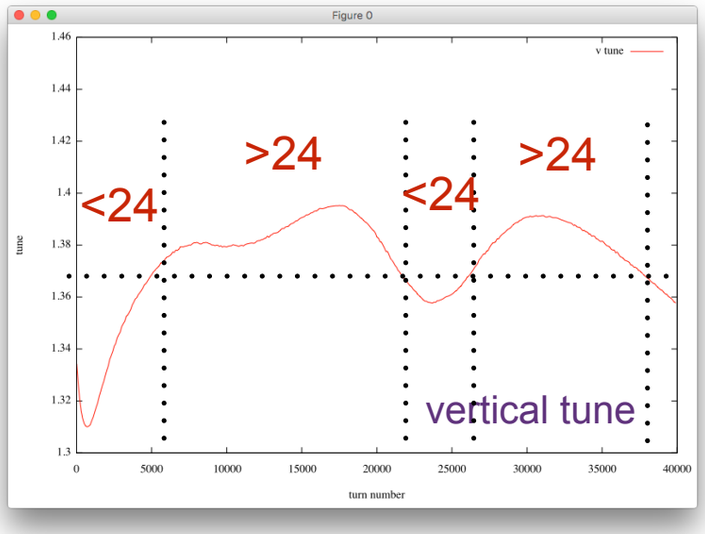
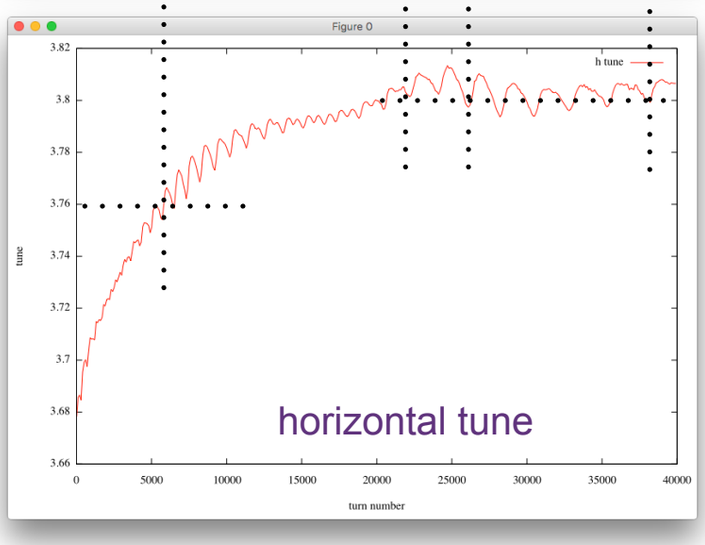
Emittance evolution with 2D and 3D field data

is this artefact or real?

Tune evolution







6Qh+Qv=2*12 7th order coupling

??

Much higher order in horizontal plane is consistent with much higher increase of horizontal emittance.

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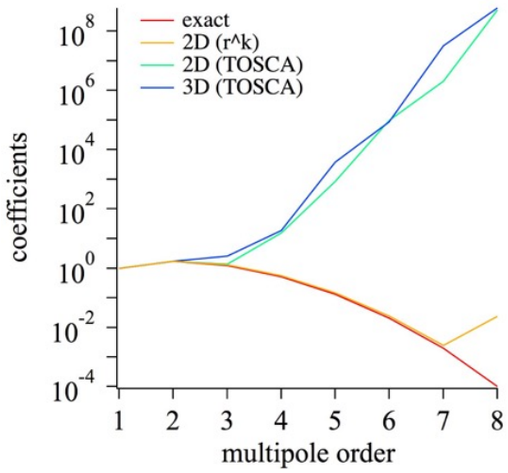
Emittance evolution with 2D and 3D field data

is this artefact or real?

All compared

Multipoles obtained from 2D and 3D TOSCA field maps are significantly different from ideal at n=4, 5 and higher.

It depends on
1. the order of vertical coordinate z^m when extrapolating from 2D.
2. the location of “rotating coil”.



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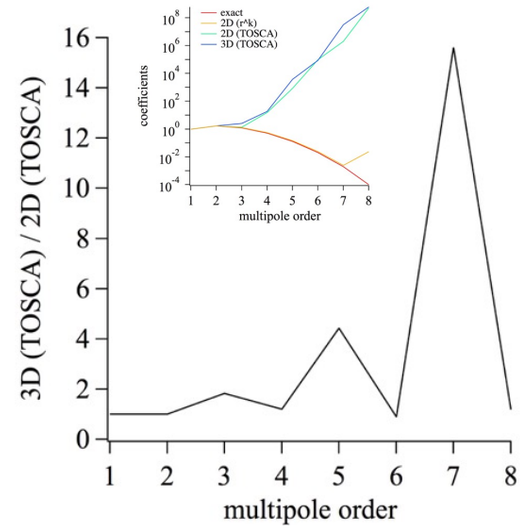
Difference between 2D and 3D

If you compared coefficients from 2D TOSCA and 3D TOSCA, odd order (sext, deca, 14 pole, …) has large difference.

This may explain the reason why the emittance jump (6Qh +Qv=2*12, 7th order coupling?) appears in 3D TOSCA field, but not in 2D TOSCA field.



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Dynamic aperture

Dynamic aperture
at injection energy

Lattice with fieldmap
at 11 MeV

Zgoubi

Lattice with fieldmap at 11MeV

Verti amplitude (mm.mrad)	Verti amplitude (cm)	Cell tune	Ring tune	Hori aperture (mm.mrad,norm)
0	0	0.3063 0.1114	3.6756 1.3368	628
1	0.51	Same	Same	605
2	0.73	Same	Same	605
3	0.89	Same	Same	605

βγ = 0.1535
βx = 0.739 m
βγ = 4.095m

At injection energy for 10 000 turns.

Same results with 2D and 3D fieldmaps.

Scode

Lattice with fieldmap
at 11 MeV

Vertical amplitude is restricted by field map (+/- 10 mm). It cannot go beyond 3 pi mm mrad (normalised).

vert amplitude [pi mm mrad]	cell tune	ring tune	hori aperture [pi mm mrad]
0	0.3066 / 0.1112	3.6791 / 1.3348	600
1	same above	same above	550
2	same above	same above	550
3	same above	same above	550

At injection energy for 10,000 turns.

2

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Some of the difference come from the resolution of the DA definition.

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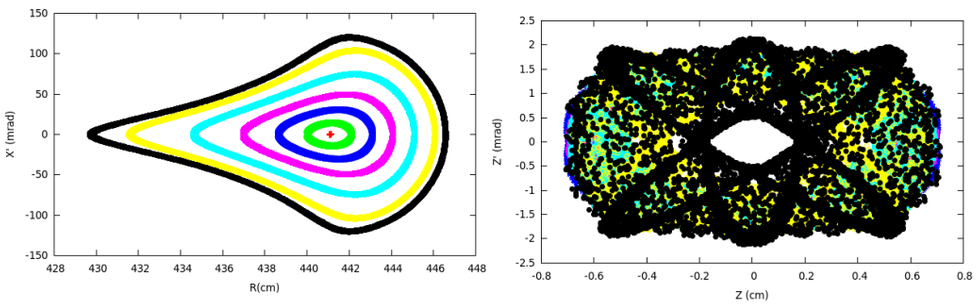
Dynamic aperture
at injection energy

Phase space at injection
at 11 MeV

Phase space at injection



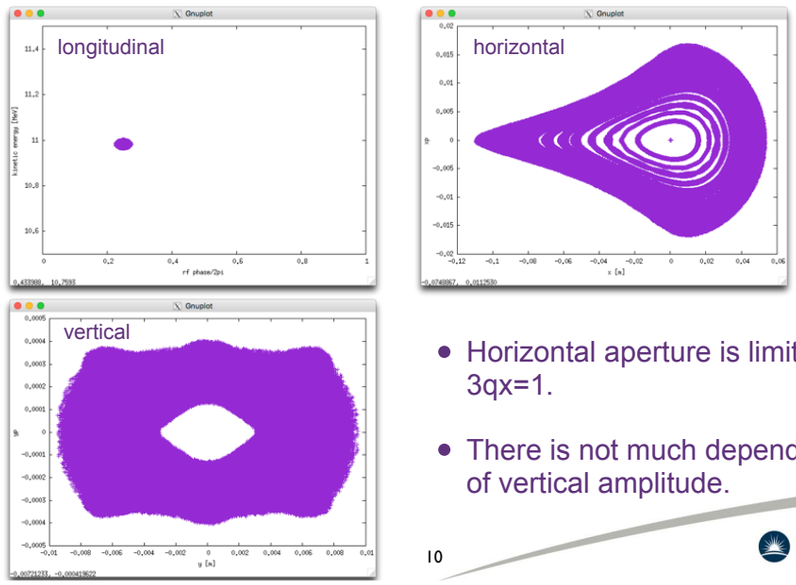
Horizontal

Vertical

Phase space at injection energy when vertical amplitude is 2 mm.mrad.

Phase space

When vertical amplitude is 3 pi mm mrad (fixed) and search horizontal aperture until a particle is lost.



- Horizontal aperture is limited by 3qx=1.
- There is not much dependence of vertical amplitude.

10

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5

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20

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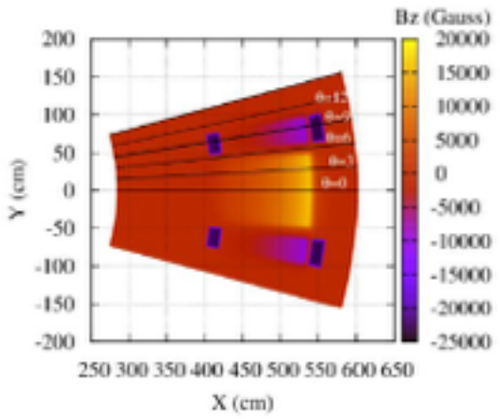
Space charge effects

FFAG with space charge effects (1)

ZGOUGI (to be updated)

Tests of the space charge module on the KURRI 150 MeV FFAG

Analytical model of the 150 MeV KURRI FFAG machine implemented in Zgoubi.



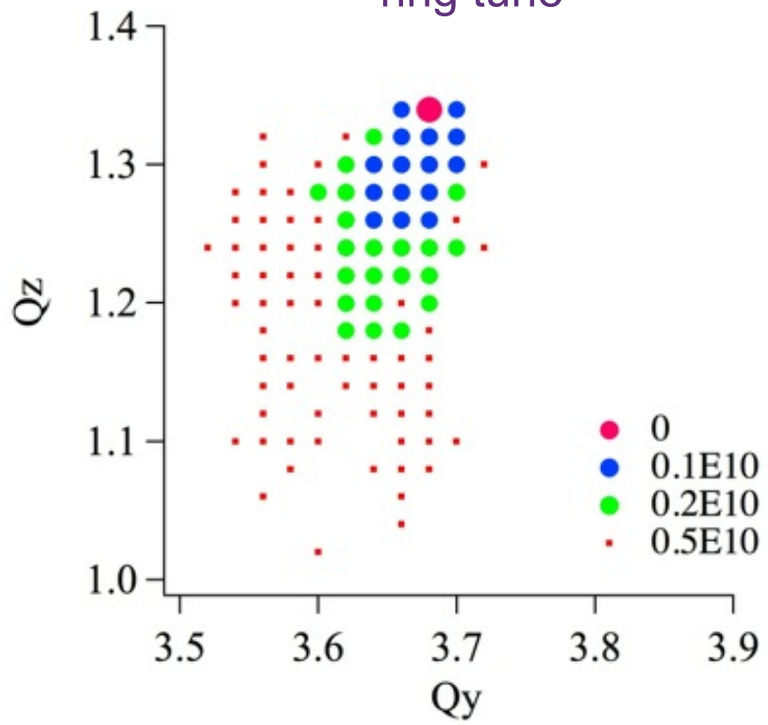

```
'FFAG'              #START                                                                  3
20
5   30.     440.48836355                    NMAG, AT=tetaF+2tetaD+2Atan(XFF/R0), R0
0.000  0.  -0.4412832  0.239148              mag 0 : ACNT, dum, B0, K                        MAGNET 1
6.3  03.                                  EFB 1 : lambda, gap const/var=0/.ne.0
4  .1455   2.2670  -.6395  1.1558  0. 0.  0.
4.7 0.    1.E6  -1.E6  1.E6  1.E6
6.3  03.                                  EFB 2
4  -3.07033892e+00, 8.59656096e+00,  -1.04829407e+01,   5.80500507e+00   0. 0.  0.
-3.6  0.    1.E6  -1.E6  1.E6  1.E6
0. -1                                     EFB 3 : inhibited by iop=0
0  0.      0.      0.      0.      0. 0.  0.
0. 0.      0.      0.      0.      0.
6.465  0.  -1.6151060  9.426756              mag 1 : ACNT, dum, B0, K                        MAGNET 2
8.3  03.                                  EFB 1 : lambda, gap const/var=0/.ne.0
5  -4.12200913e-01   2.22904985e+00  -6.80512267e-01 1.23609453e-01 -7.87155179e-03  0.  0.
+2.5  3.1    1.E6  -1.E6  1.E6  1.E6
6.3  03.                                  EFB 2
4  -8.23066935e-01, 2.36019103e+00,  -3.84298625e-01,   2.43560489e-01  0. 0.  0.
-1.765  0.    1.E6  -1.E6  1.E6  1.E6
0. -1                                     EFB 3 : inhibited by iop=0
0  0.      0.      0.      0.      0. 0.  0.
0.  0.   0.    0.    0. 0.
15.   0.   3.400519, 7.707476                   mag 2 : ACNT, dum, B0, K,dummies            MAGNET 3
6.3  03.                                  EFB 1
4   -4.13707399e-01,   2.14307057e+00, -4.26620705e-01,   1.70354587e-01  0. 0.  0.
5.37   0.    1.E6  -1.E6  1.E6  1.E6
6.3  03.                                  EFB 2
4   -4.13707399e-01,   2.14307057e+00, -4.26620705e-01,   1.70354587e-01   0.  0.  0.
-5.37   0.    1.E6  -1.E6  1.E6  1.E6
0. -1                                     EFB 3
0  0.      0.      0.      0.      0. 0.  0.
0.  0.   0.    0.    0. 0.
23.535  0.0  -1.615106,  9.426756             mag 3 : ACNT, dum, B0, K                        MAGNET 4
6.3  03.                                  EFB 1
4   -8.23066935e-01, 2.36019103e+00,  -3.84298625e-01,   2.43560489e-01  0. 0.  0.
1.765  0.    1.E6  -1.E6  1.E6  1.E6
8.3  3.                                   EFB 2
5   -4.12200913e-01   2.22904985e+00  -6.80512267e-01  1.23609453e-01   -7.87155179e-03  0.   0.
-2.5  -3.1    1.E6  -1.E6  1.E6  1.E6
0. -1                                     EFB 3
0  0.      0.      0.      0.      0. 0.  0.
0.  0.   0.    0.    0. 0.
30.  0.  -0.4412832  0.239148               mag 4 : ACNT, dum, B0, K                        MAGNET 5
6.3  03.                                  EFB 1 : lambda, gap const/var=0/.ne.0
4  -3.07033892e+00, 8.59656096e+00,  -1.04829407e+01,   5.80500507e+00  0. 0.  0.
3.6 0.    1.E6  -1.E6  1.E6  1.E6
6.3  03.                                  EFB 2
4  .1455   2.2670  -.6395  1.1558  0. 0.  0.
-4.7  0.    1.E6  -1.E6  1.E6  1.E6
0. -1                                     EFB 3 : inhibited by iop=0
0  0.      0.      0.      0.      0. 0.  0.
0.  0.   0.    0.    0. 0.
2  2  125.                KIRD anal/num (=0/2.25.4), resol(mesh=step/resol)
```

FFAG with space charge effects (2)
SCODE

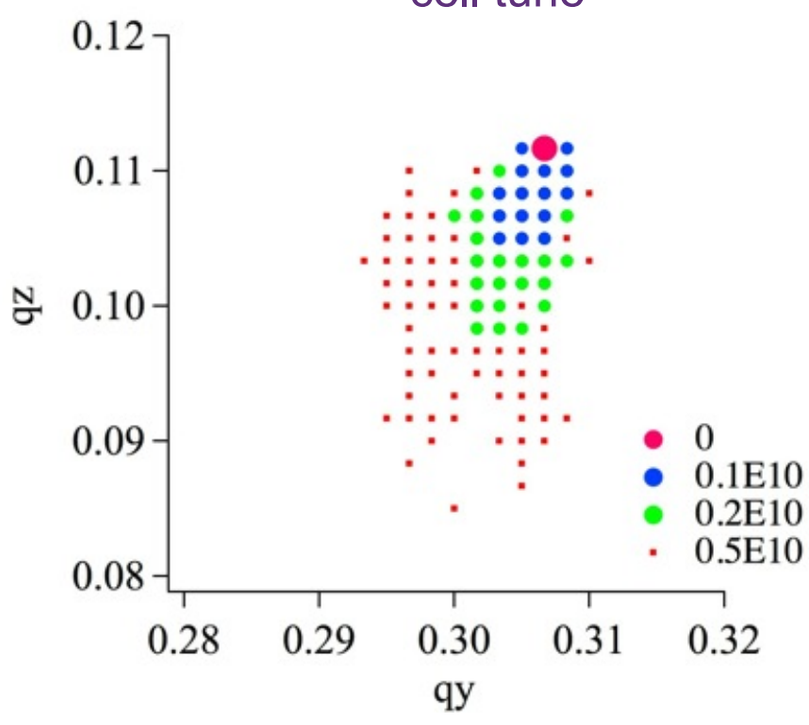
Benchmark step2 results
with space charge

Space charge tune spread for the first 50 turns

ring tune



cell tune



n_t	Delta Q
0.1x10	-0.11
0.2x10	-0.21
0.5x10	-0.54

Agreed with the formula.

except for 0.5E10 when emittance changes significantly (next page).

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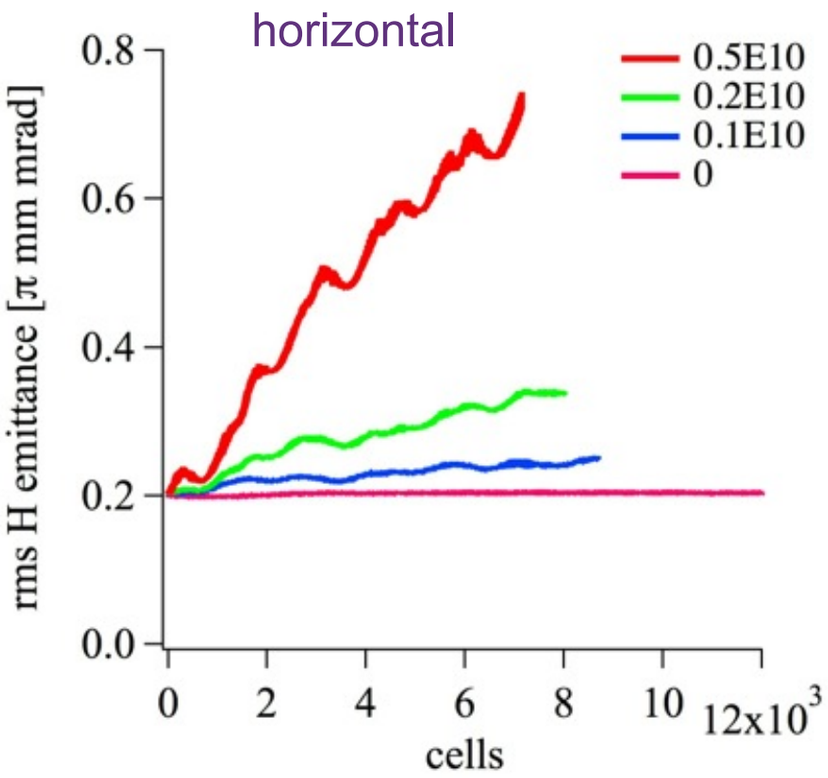
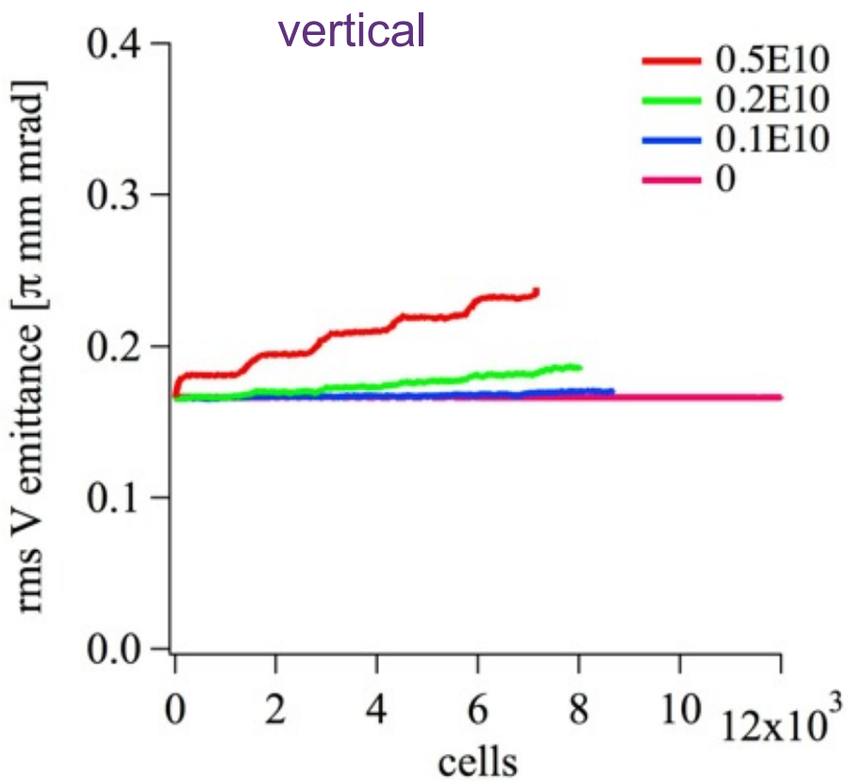
FFAG with space charge effects (3)
SCODE

Benchmark step2 results
with space charge

Emittance evolution of the first 1000 turns with acceleration.





Increase by a step corresponds to a half synchrotron oscillation. (~1,300 cells)

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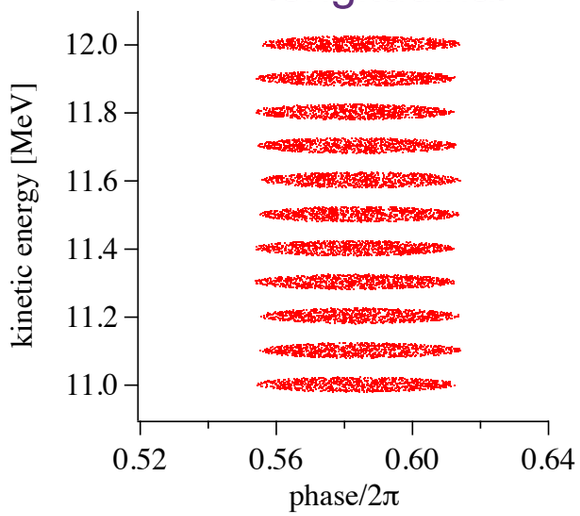
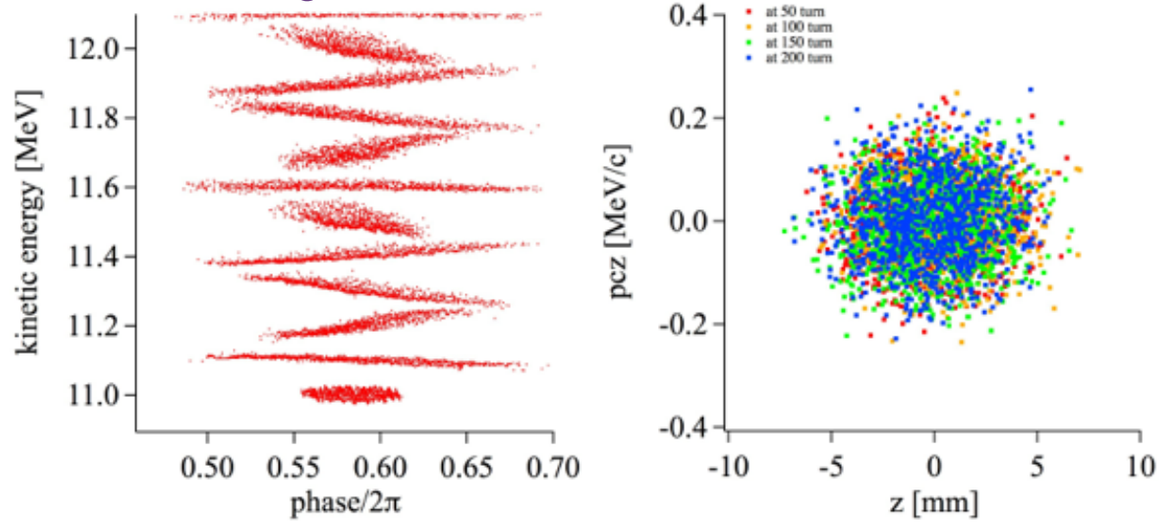
FFAG with space charge effects (4)
SCODE

Benchmark step2 results
with space charge

without space charge



with 0.5E10



- Quadrupole oscillation in longitudinal phase space is the source of stepwise emittance growth in transverse.
- This can be eliminated with initial condition.
- No coherent oscillation in transverse phase space.

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Remarks

- Boundary condition, e.g. flat plate below and above the orbits becomes importance, especially for multi bunches at the same.

- Zero chromaticity is nice as scaling FFAG, but instability issues becomes issues once the beam current increases.

Summary

KURRI FFAG simulation

	ZGOUBI	SCODE	OPAL	EARLIETIMES	MAUS
transverse tune	agreed	agreed	agreed	agreed	agreed
longitudinal motion	agreed	agreed	capable but not benchmarked	—-	—-
emittance evolution	agreed	agreed	—-	—-	—-
dynamics aperture	agreed	agreed	—-	look similar but not benchmarked	—-
space charge	under development	under development	—-	—-	—-

- TOSCA 3D (2D) data map with finer mesh and more details is planned.
- Dynamic aperture measurement should be tried.