High Power Ring Methods and Accelerator Driven Sub-critical Reactor application

[1]François Méot and [2]M. Haj Tahar

[1]Collider Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973

[2]Center for Radiological Research, Columbia University Medical Center, New York, NY 10032

ABSTRACT

The focus of this work is on the high power ring methods in the frame of the KURRI FFAG collaboration in japan. Upgrade of the installation towards high intensity is crucial to demonstrate the high beam power capability of FFAG. Thus, modeling of the beam dynamics and benchmarking of different codes was undertaken to validate the simulation results. Experimental results revealed some major losses that need to be understood and eventually overcome. By developing analytical models that account for the field defects, one identified major sources of imperfection in the design of scaling FFAG that explain the important tune variations resulting in the crossing of several betatron resonances. A new formula is derived to compute the tunes and properties established that characterize the effect of the field imperfections on the transverse beam dynamics. The results obtained allow to develop a correction scheme to minimize the tune variations of the FFAG. This is the cornerstone of a new fixed tune non-scaling FFAG that represents a potential candidate for high power applications.

INTRODUCTION

In recent years, the concept of Accelerator Driven Sub-critical Reactor (ADSR) has gained more interest worldwide as a potential candidate to solve the problem of nuclear waste. This concept, the focus of the present dissertation, requires the coupling of a high power proton accelerator with a sub-critical core. Among the many options that can serve as a proton driver, the Fixed Field Alternating Gradient (FFAG) accelerators. The work presented in this thesis is dedicated to demonstrate the high power capability of FFAGs.

RBENCHMARKING OF DIFFERENT SIMULATION CODES FOR KURRI 150 MeV SCALING FFAG

Scaling FFAG at KURRI was commissioned and delivered the first beam in 2009. Since then, several upgrades took place to demonstrate the high beam power capability of FFAG.

Specifications of the KURRI FFAG	
Focusing structure	DFD
N_{cells}	12
Injection energy	11 MeV
Extraction energy	100 →150 MeV
Average radius	4.57 → 5.4 m
Field index k	7.6
Average current (inj)	600 nA
Beam transmission	**0.25 %**

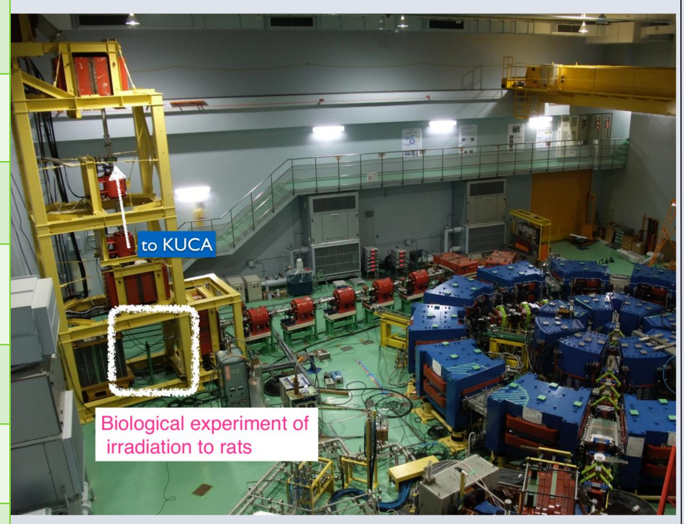

Fig 1. FFAG complex at KURRI.

Following the FFAG'14 workshop held at BNL, a simulation campaign was established to benchmark several simulation codes. The main objective is to provide reliable modeling tools for FFAG and to explain the results of the experiments at KURRI.

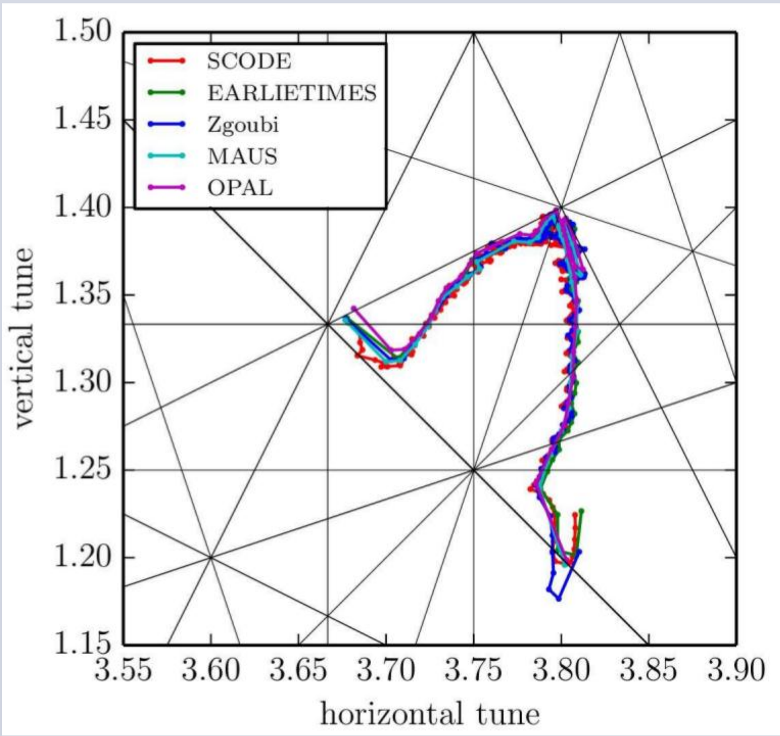

Fig 2. Betatron tunes from 11 to 139 MeV (left to right) calculated with several codes. The Zgoubi model is in good agreement with the others

Beam transmission	
Injection efficiency	40 %
Transmission up to 1 ms	2.5 %
Transmission from 1 ms to extraction	25 %
Extraction efficiency	100 %
Overall transmission	0.25 %

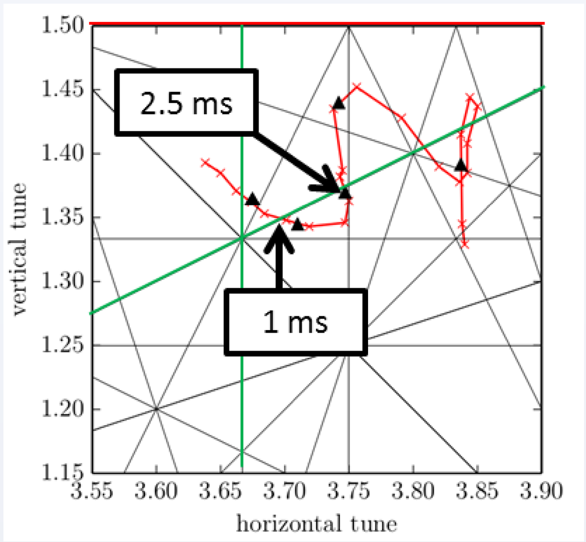

Fig. 3 Measured tunes and timing of major beam losses at the KURRI FFAG.

Major beam losses due to resonance crossing. How to explain the tune variations observed both experimentally and numerically?

BEAM STABILITY ANALYSIS

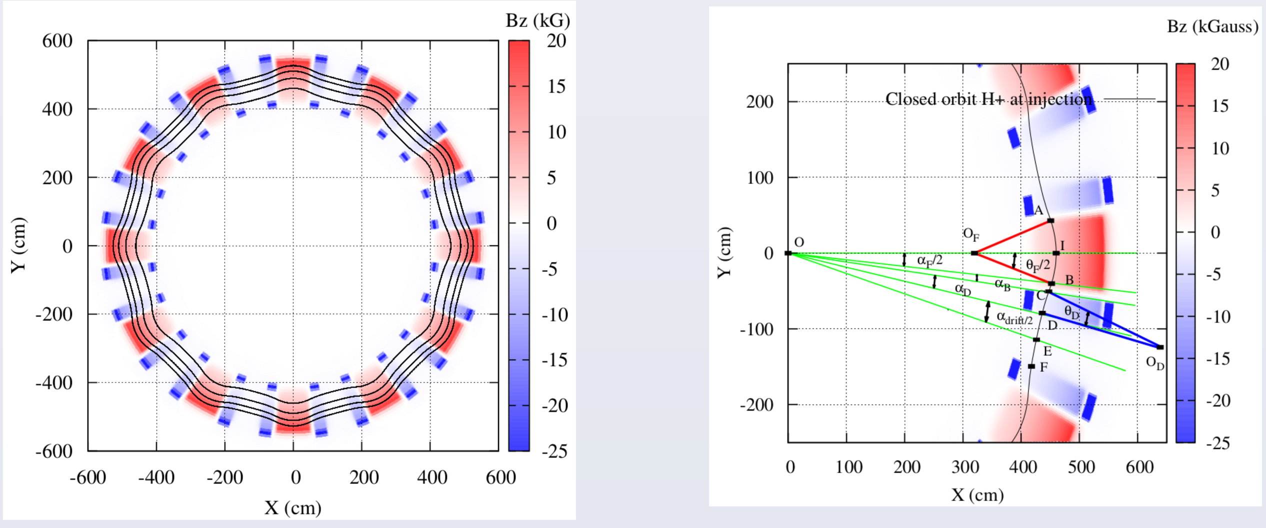

Fig. 4 Example of trajectory in the hard edge model.

Define an extension of the mean field index of the magnet by introducing its azimuthal variations through the F and D magnets, i.e k_F and k_D. In the ideal case, $k_F = k_D$.

Mainly found that due to the cross-talk between the F and D magnets, the field index is different from the ideal one.

Using the BKM's method of averages, one showed that:

$$\begin{cases} \nu_x^2(E) = \sum_i \beta_i(E) - \sum_i \alpha_i(E) \times k_i(E) \\ \nu_y^2(E) = \sum_i \alpha_i(E) \times k_i(E) + \mathcal{F}^2\left[1 + 2\tan^2(\xi)\right] \end{cases}$$

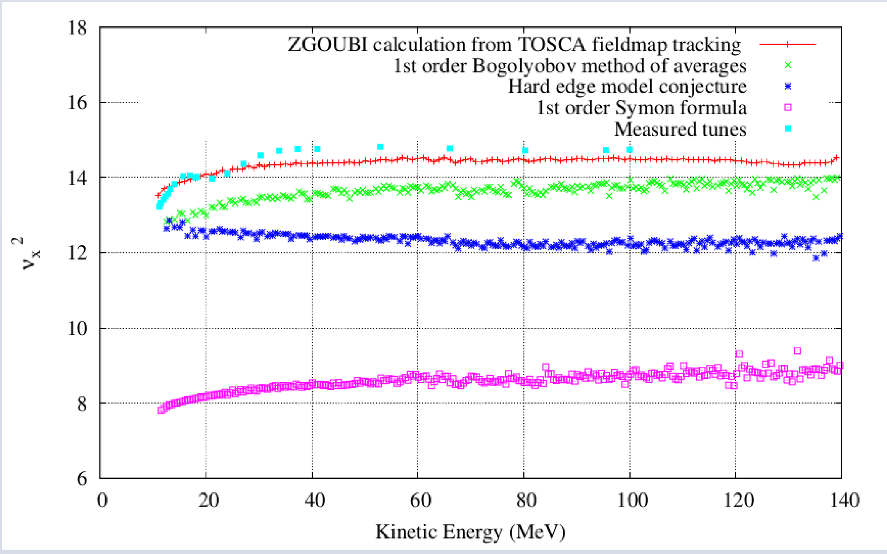

Fig 5. Tune calculation in the horizontal plane and comparison with the analytical formula.

Key finding:

I. *In presence of scaling imperfections, the number of betatron oscillations per turn* ***increases*** *(resp decreases) with the energy* ***if*** $\boldsymbol{\kappa = k_D - k_F > 0}$ *(resp* $\boldsymbol{\kappa < 0}$*).*

II. *Besides, the RMS tune variations are, to the first order, proportional to* $|\boldsymbol{\kappa}|$.

Results demonstrated analytically and through numerical simulations.

Can we combine these two effects in one single lattice to obtain a fixed tune FFAG?

CORRECTION SCHEME AND ADVANCED ACCELERATOR CONCEPTS

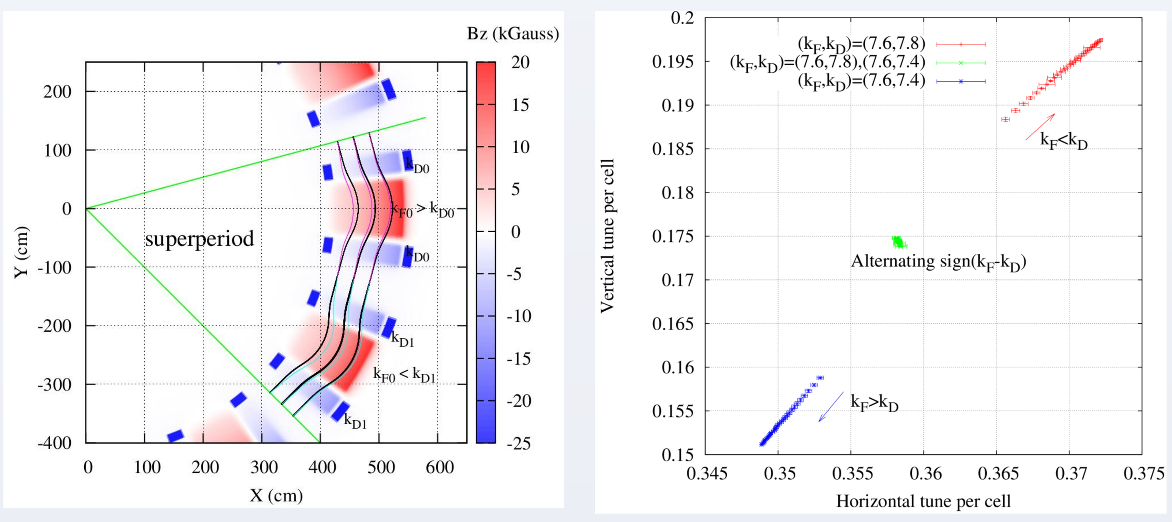

Fig 6. Closed orbits in the fixed tune non-scaling FFAG concept.

By alternating scaling imperfections, one can remediate the tune variations in FFAG. This is the cornerstone of the new FFAG concept and demonstrates that the cardinal conditions of scaling FFAG are non-necessary conditions to obtain a fixed tune FFAG.

DYNAMIC ACCEPTANCE

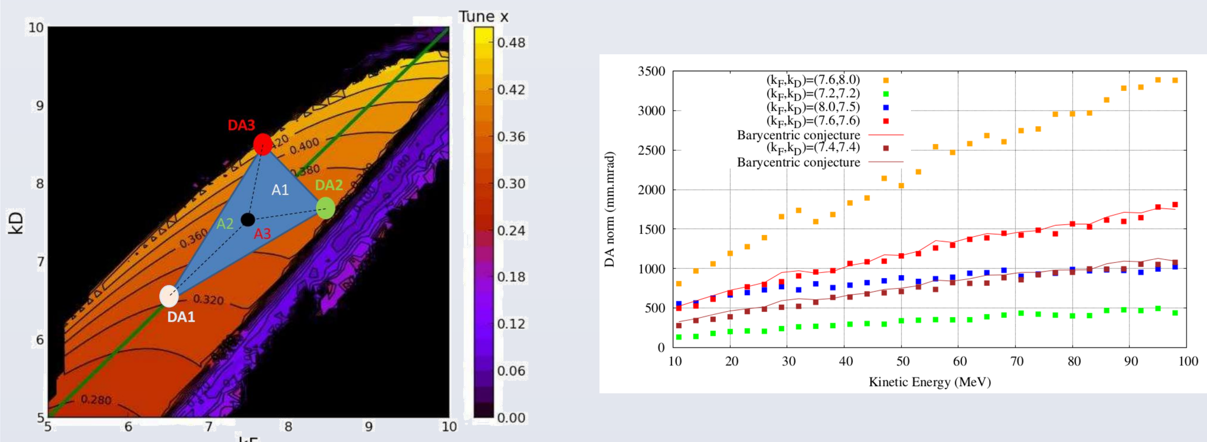

Fig 7. Schematic of the 2D barycentric interpolation method.

$$DA(k_F, k_D) = \lambda_1 DA(k_{F1}, k_{D1}) + \lambda_2 DA(k_{F2}, k_{D2}) + \lambda_3 DA(k_{F3}, k_{D3})$$

where $\lambda i = Ai/(A1 + A2 + A3)$

⇨Good agreement between the simulated and the conjectured results.

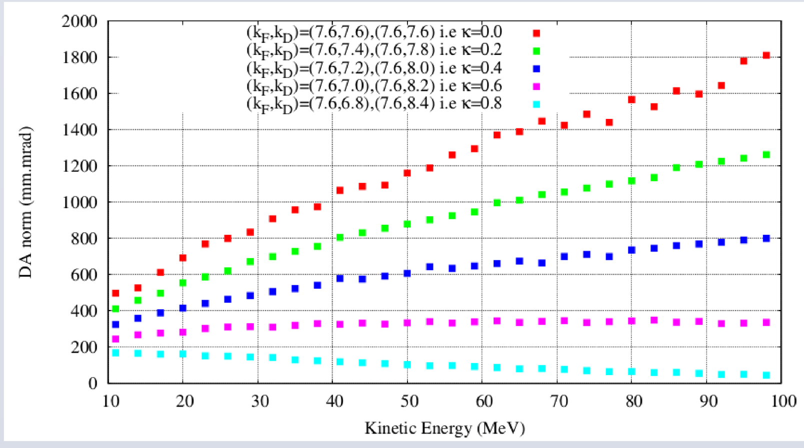

Fig 8. DA of the fixed tune non-scaling FFAG concept.

CONCLUSION

- In KURRI, characterization of the experiments is still on-going.
- Benchmarking of different simulation codes yielded excellent agreement.
- Major beam losses were observed, mainly due to resonance crossings.
- Both analytical and simulation models were developed which demonstrated that the tune variations obey a well defined law involving the non-scaling of the orbits.
- A correction scheme is presented which allows to overcome the resonance crossings and is the new concept of the fixed tune non-scaling FFAG.
- It is shown that the DA is lower with increasing scaling imperfections in this concept.

REFERENCES

[1] M. Haj Tahar, High Power Ring Methods and Accelerator Driven Subcritical Reactor application, PhD dissertation, BNL-113766-2017-TH; March 2017.