FFAG as an energy efficient proton driver

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Overview

- Energy efficiency in high beam power accelerator.
- Fixed field alternating gradient (FFAG) accelerator
- Optimised design as a proton driver of 3 GeV.
- 10 years R&D plan
- Summary

Workshop on the energy efficiency of proton driver accelerators

- **High power proton drivers** are needed to generate secondary particles at high intensities, such as neutrons, muons or neutrinos.
- The applications of these facilities have a broad spectrum in the fields of particle physics and condensed matter physics. On the other hand, the production of megawatt-class proton beams implies the consumption of large amounts of electrical energy. This aspect is seen more and more critical in the public society and in funding agencies. New projects and operating facilities must focus on **improving the energy efficiency with a higher priority**. With this workshop we are aiming to supporting such developments towards higher efficiency.
- The anticipated needs of secondary particle flux for experimental applications will be reviewed, as well as **intrinsic efficiency aspects of different accelerator concepts**, suited for high power beam production.

High power proton drivers

Our target is high efficiency in a high power proton driver, not a high energy accelerator.

Figure of merit: M = (Beam power) / (Electricity per unit time)

Beam power = (Beam energy) x (Repetition rate) x (# of particle per pulse)

- **Beam energy**
  - There is optimum for secondary particle production.
  - Typically, 1 - 10 GeV.
- **Repetition rate**
  - CW is the best to increase average power.
  - Some applications (e.g. pulsed neutron users) do not accept CW beams.
- **# of particle per bunch/pulse**
  - As small as possible.
  - Space charge effects limit # of particle below a few x $10^{13\text{-}14}$ per bunch.

Target parameters

Energy:	1 - 10 GeV
Average current:	1 - 10 mA
Repetition rate:	CW or as high as possible
Type:	Linear or Circular accelerator

Linear or Circular

Energy consumption in a circular accelerator

- Energy consumption in **accelerating cavities**.
  - Energy has to be provided to accelerate beams.
  - Energy conservation law cannot be challenged. If one wants 1 MW beams, one has to give at least 1 MW in the cavities.
  - Cavities and beam require additional amount of energy.

- Energy consumption in **lattice magnets**.
  - Magnets in circular accelerators do not contribute to acceleration.
  - Energy consumption should be minimised. Ideally zero.
  - Goal is no energy requirement for the lattice. Then no difference between linac and a circular accelerator.

	beam power (MW)	RF (MW)	magnets (MW)
ISIS	0.18	2	1.5
J-Parc RCS	0.5	6.8	9.7
ideal	p	$(1 + f) \times p$, f **~ 0**	**~ 0**

Linear or Circular

Energy consumption in a linear accelerator

- Energy consumption in **accelerating cavities**.
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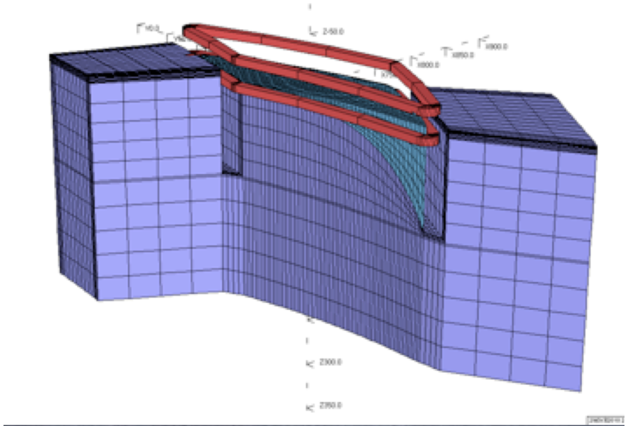
ideal	p	$(1 + f) \times p$, f **~ 0**	**~ 0**

Situation becomes the same if the lattice magnets in circular accelerators do not need electricity?
Is there any additional constraints on either accelerator? Stability criteria? Make any difference due to different frequency?

DC magnets

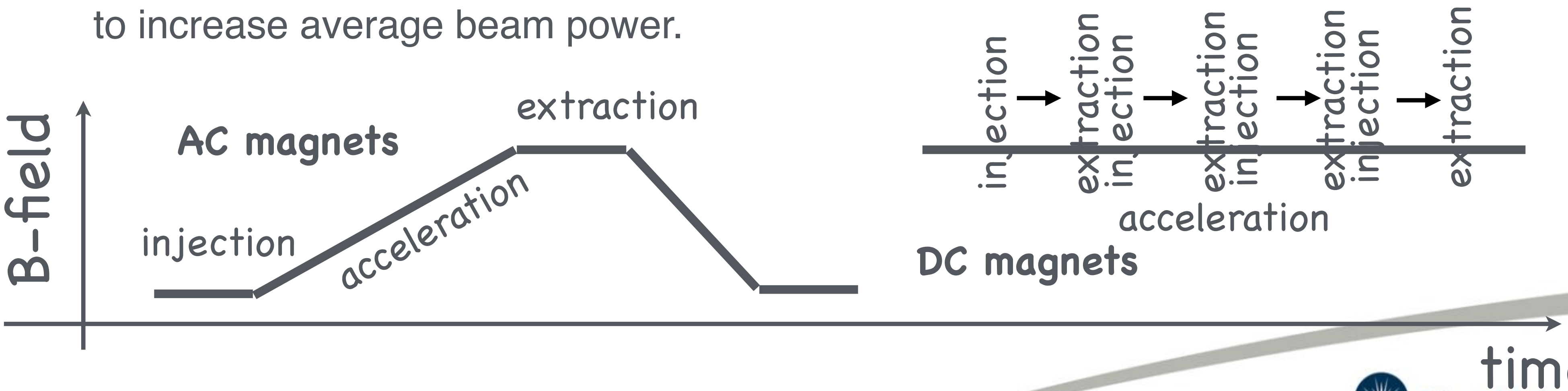
Circular accelerators should use DC magnets.

- Use of superconducting magnet or permanent magnet can be considered as an obvious option to reduce energy consumption in the main lattice.



Goal is a magnet with cryocooler (standalone cooler).

- Higher repetition rate of operation (without ramping of magnets) can be considered to increase average beam power.



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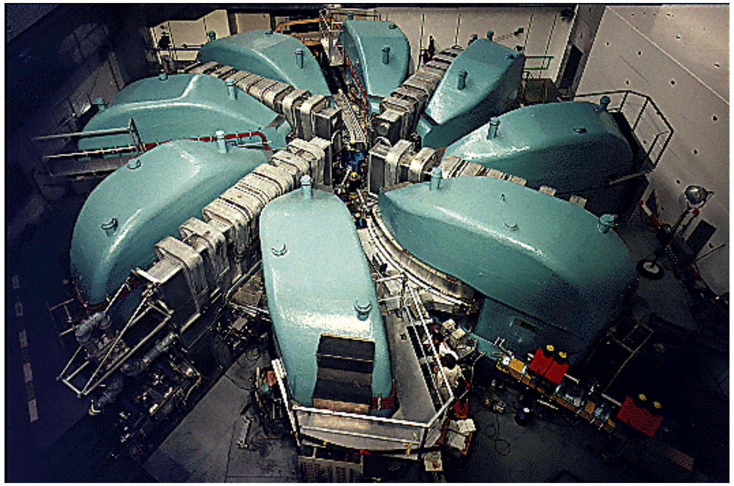
Cir acc with DC magnets

- Cyclotron is an example.
  - Magnet is DC and beams are accelerated continuously with RF micro structure of ~50 MHz.
  - Energy is limited below 1 GeV.



PSI

- Fixed Field Alternating Gradient (FFAG) accelerators is another candidate.
  - Can have CW operation like cyclotrons, but then no different from cyclotrons.
  - Can be 100 Hz or more, only be limited by the available RF power.
  - Energy can easily go beyond 1 GeV.

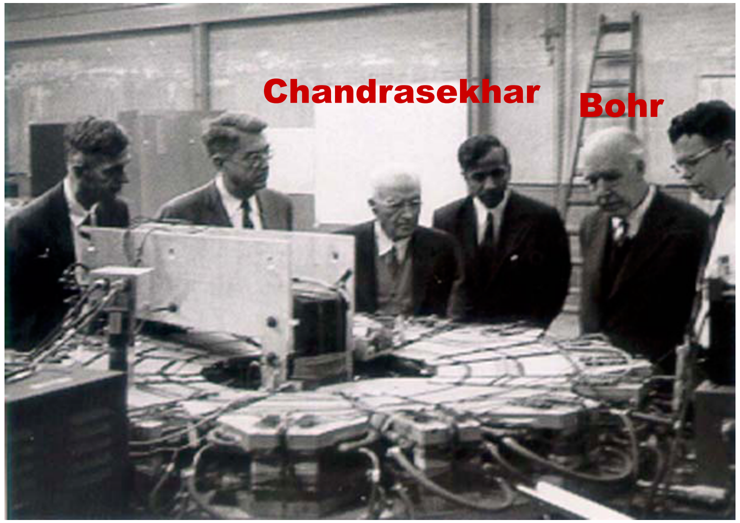
i.e. High energy synchro-cyclotron without increasing the magnet size.

Ideal circular accelerator

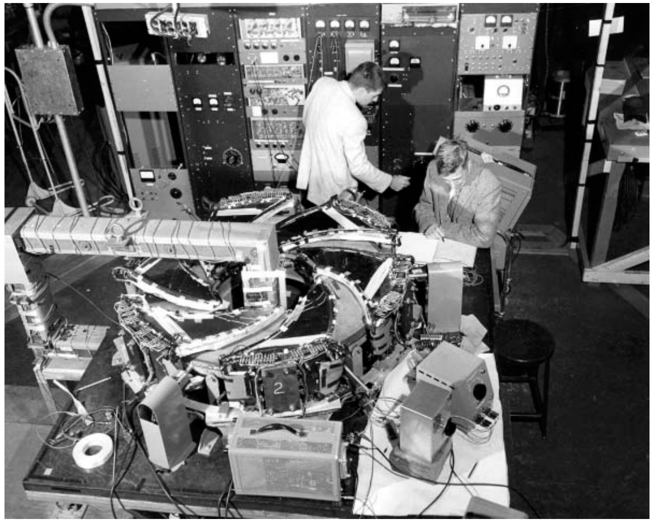
What is FFAG?

What is FFAG?

- Proposed in 1950s.
  - ~10 years development at MURA.
  - Rebirth in 2000.
  - EMMA at Daresbury in 2012.
- Similar to cyclotrons.
  - DC magnet.
  - Orbit spirals out.
- Similar to synchrotrons.
  - Alternating gradient (AG) focusing makes small beam size.
  - Orbit excursion from injection to extraction is minimised.
  - Transverse tune is constant.
  - Pulsed mode operation with single turn extraction.



400 keV radial sector



180 keV spiral sector

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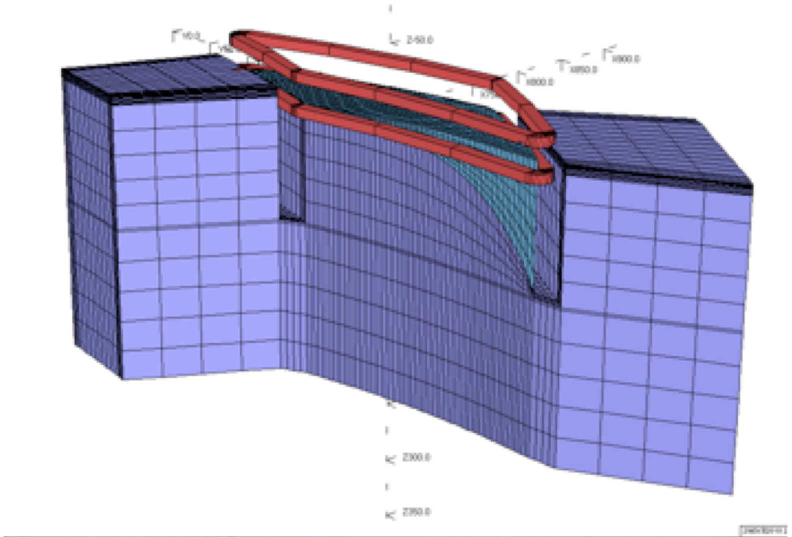
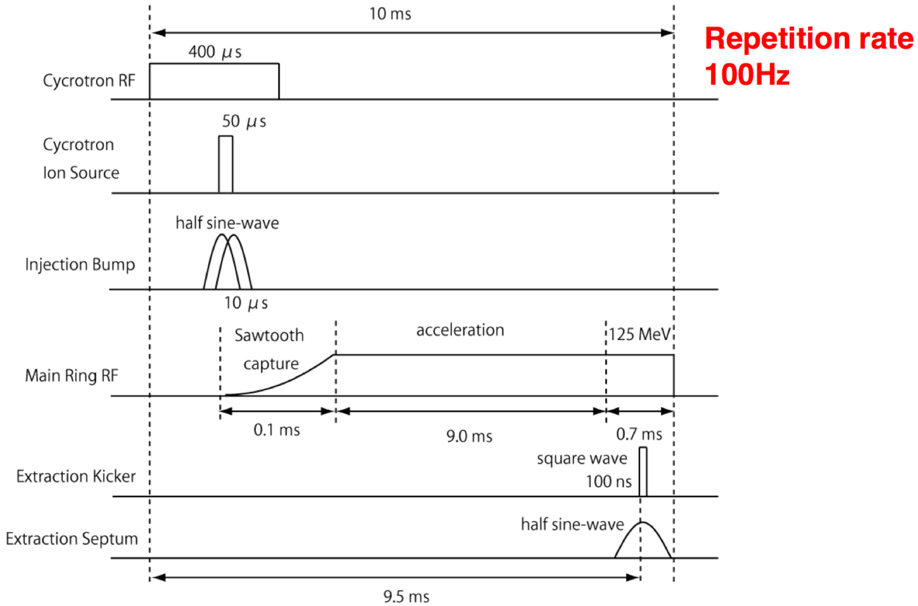
Pros (1)

- Reasonable size (smaller than cyclotron) of DC magnets.
- Low operation cost due to superconducting (superferric) or permanent magnets.
  - Keep the field strength moderate (~2 T) so that accelerator size is similar to synchrotrons.
  - Cryo-cooler operation is the goal.



Timing Chart of injector and FFAG

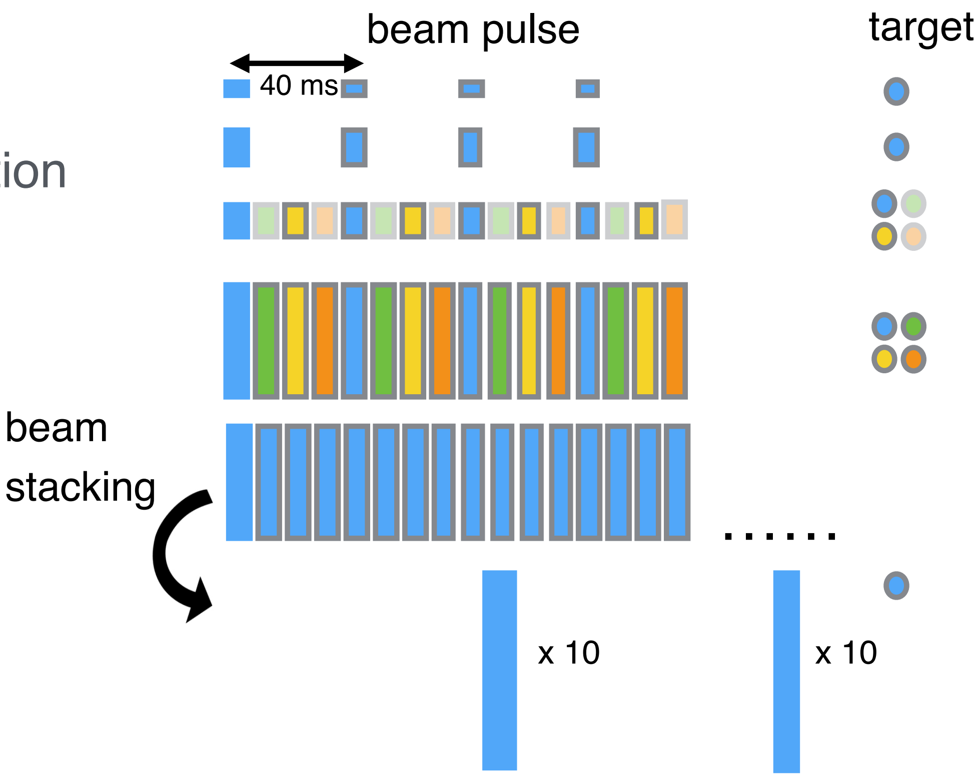


- Average beam power increases by high repetition operation.
- CW operation is not aimed (CW FFAG becomes very much like a cyclotron), but there is longitudinal focusing and bucket.

Pros (2)

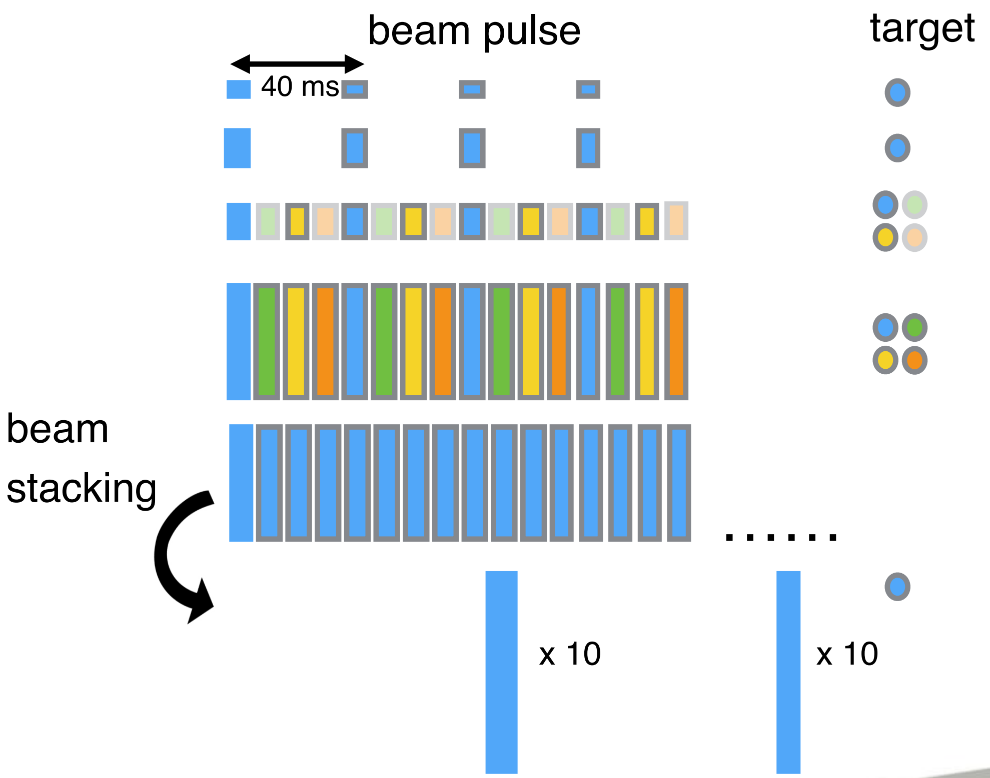
- FFAG has both accelerator and storage ring in a single circular lattice.
  - Output beam pulse structure can be controlled by RF programme.
  - For example, beam stacking at the extraction energy can produce lower rep rate pulse.

- Staged beam power up with a proper RF installation scenario.
  - Repetition rate and beam intensity are controlled by RF, not the lattice magnets.
  - Adding RF cavities in line with 1) user request, 2) target readiness, 3) beam loss handling, etc.



Pros (3)

- For target test only,
  - 1 Hz with the same bunch charge for the final goal by stacking small charge to simulate the maximum peak intensity.
  - 100 Hz with lower peak charge to to simulate the maximum average intensity.



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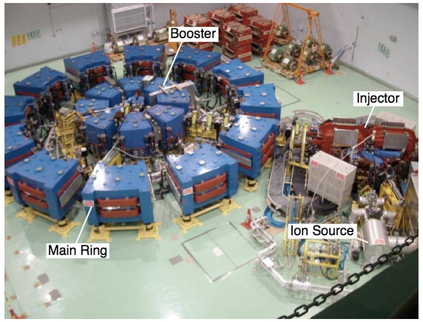
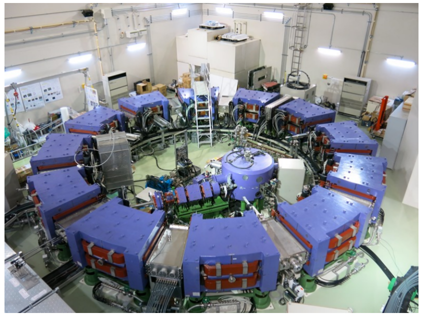
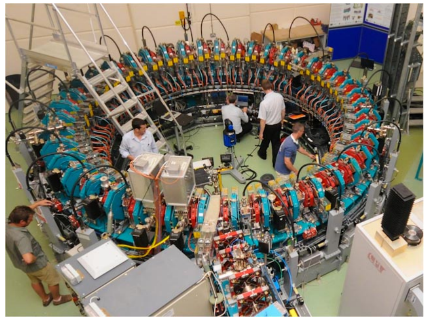
Cons

- Only two machines are in operation and they are still not high intensity.
  - One is at Kyoto University and the other at Kyushu University.
  - EMMA at Daresbury stopped operation. It was not for a proton driver anyway.



Kyoto University


Kyushu University


EMMA at Daresbury

- Optics is rather primitive.
  - Lossless (beam) injection should be studied.
  - Enough and sufficient control knobs should be established for daily user operation.
  - Many great ideas (e.g. beam stacking) exist, but not demonstrated.

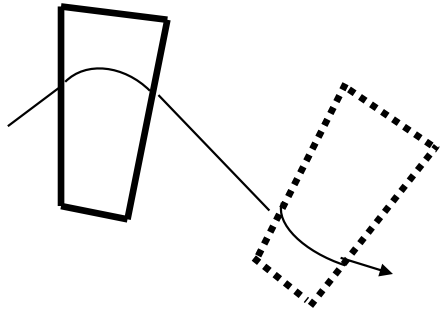
- As a proton driver, we need research and developments.

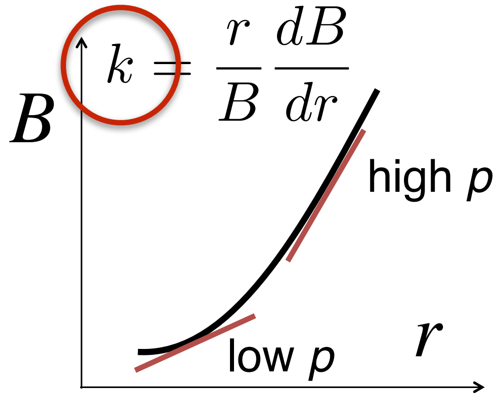
Example of a FFAG proton driver

w/ new idea on lattice

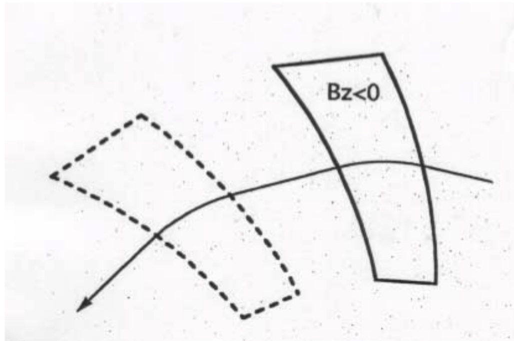
Radial or Spiral FFAG

radial sector





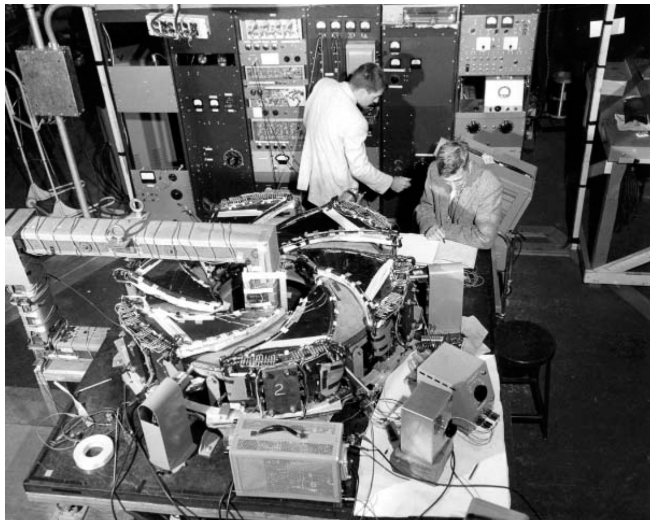
spiral sector



Alternating gradient focusing by focusing (normal bend) and defocusing (reverse bend)

Alternating gradient focusing by focusing (normal bend) and defocusing (edge angle)

400 keV radial sector



180 keV spiral sector

Radial or Spiral FFAG

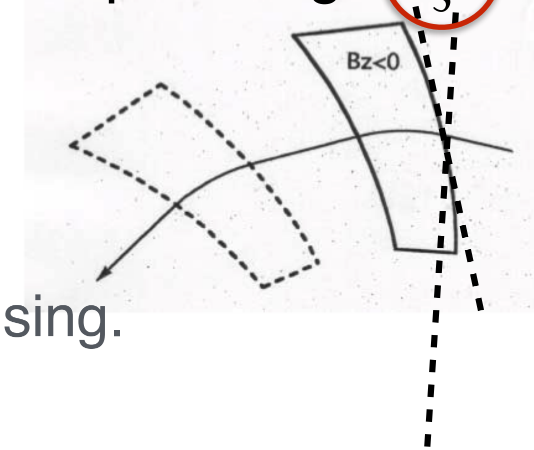
Advantage of spiral FFAG

- No reverse bending makes small footprint.

Disadvantage

- Weaker focusing in vertical.
    - need large spiral angle.
    - long fringe field extent leads to less focusing.
- No knob for tune adjustment.

spiral angle ζ



Tune is approximately (c.f. Symon, et. al., Phys Rev. 1956)

$$Q_x^2 = k + 1$$
$$Q_z^2 = -k + f^2 \tan^2 \zeta$$

where

k field index
ζ spiral angle
f field flutter

$$B = B_0 (r/r_0)^k \{1 + f \cos[N\theta - N \tan\zeta \ln(r/r_0)]\}$$

when # of cell N >> 1

$$\tan\zeta \approx \sqrt{k} \approx N$$

e.g. $N = 12 \;\; \zeta = 58^\circ$

$\Leftrightarrow$ $N = 36 \;\; \zeta = 78^\circ$

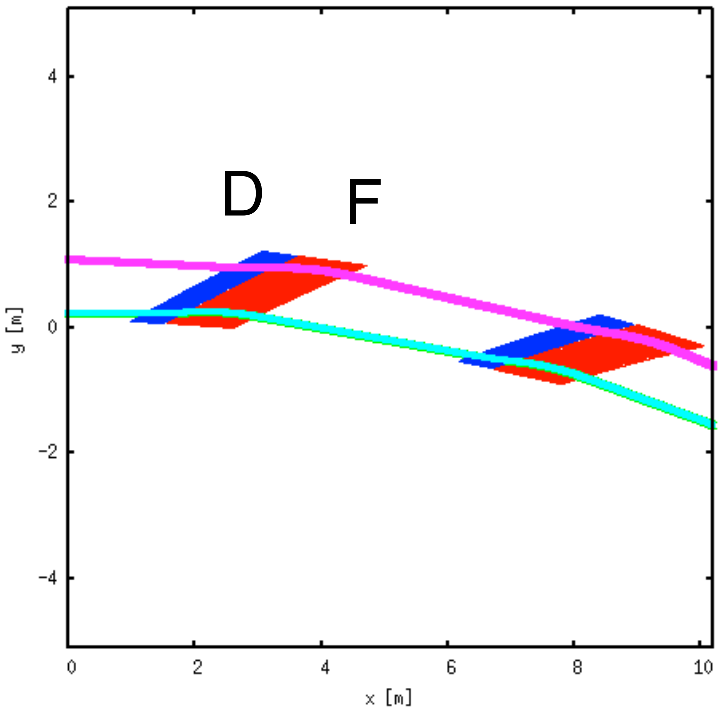
More difficult for high energy machine with large N.

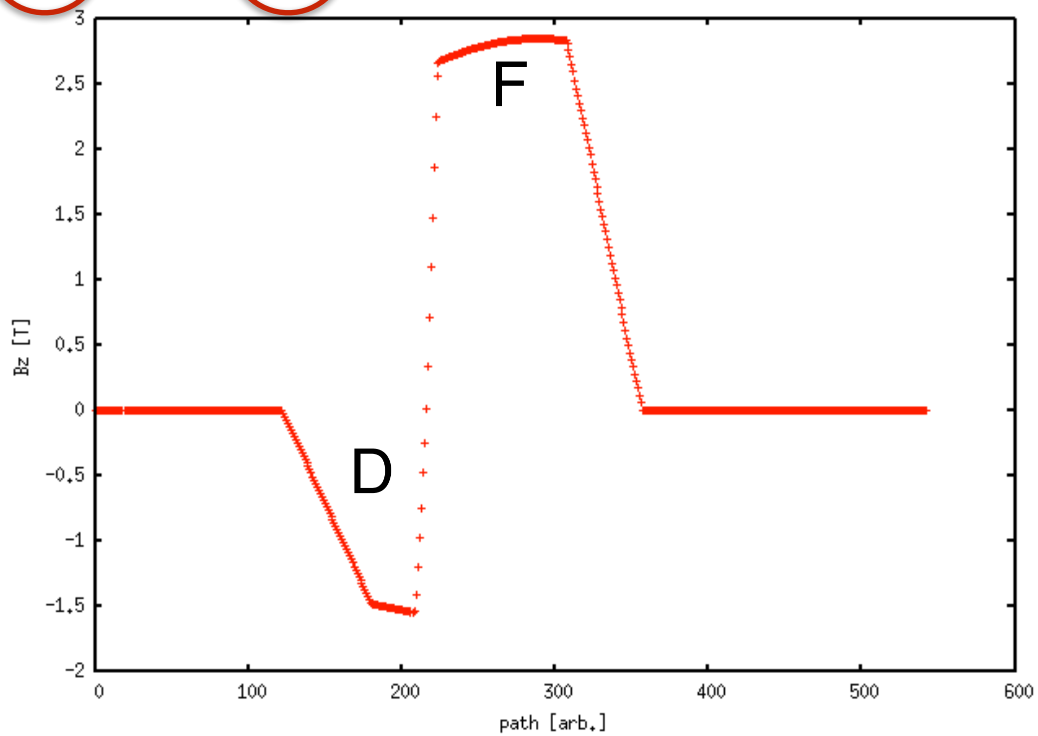
DF-Spiral FFAG

New idea: *DF-Spiral*

- Introduce (small) negative field on one side of the main spiral magnet to strengthen vertical focusing both from spiral angle and flutter factor.

$$Q_z^2 = -k + f^2 \tan^2 \zeta$$





- Shape edge is created between D and F.
- Field flutter increases.
- Knob of F/D ratio like radial type.

Parameter search (1)

Some assumption

kinetic energy	0.4 to 3 GeV
# of cell	36
radius	~ 30 m
k value	50
packing factor	0.3 ~ 0.4
size of magnet	D:F=1:2

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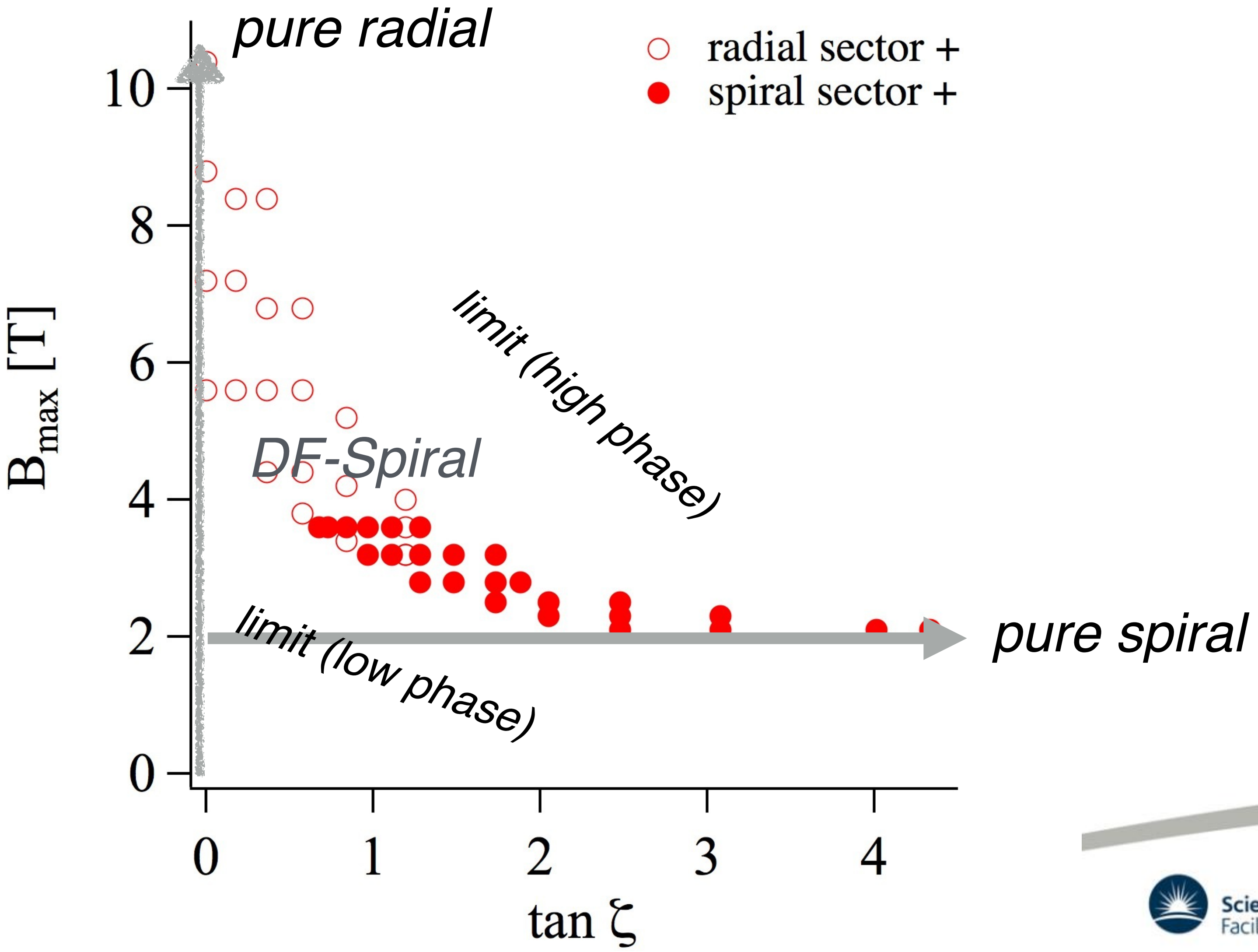
Parameter search (2)

Practically, the best parameter is obtained with the balance between B_max field and spiral angle.



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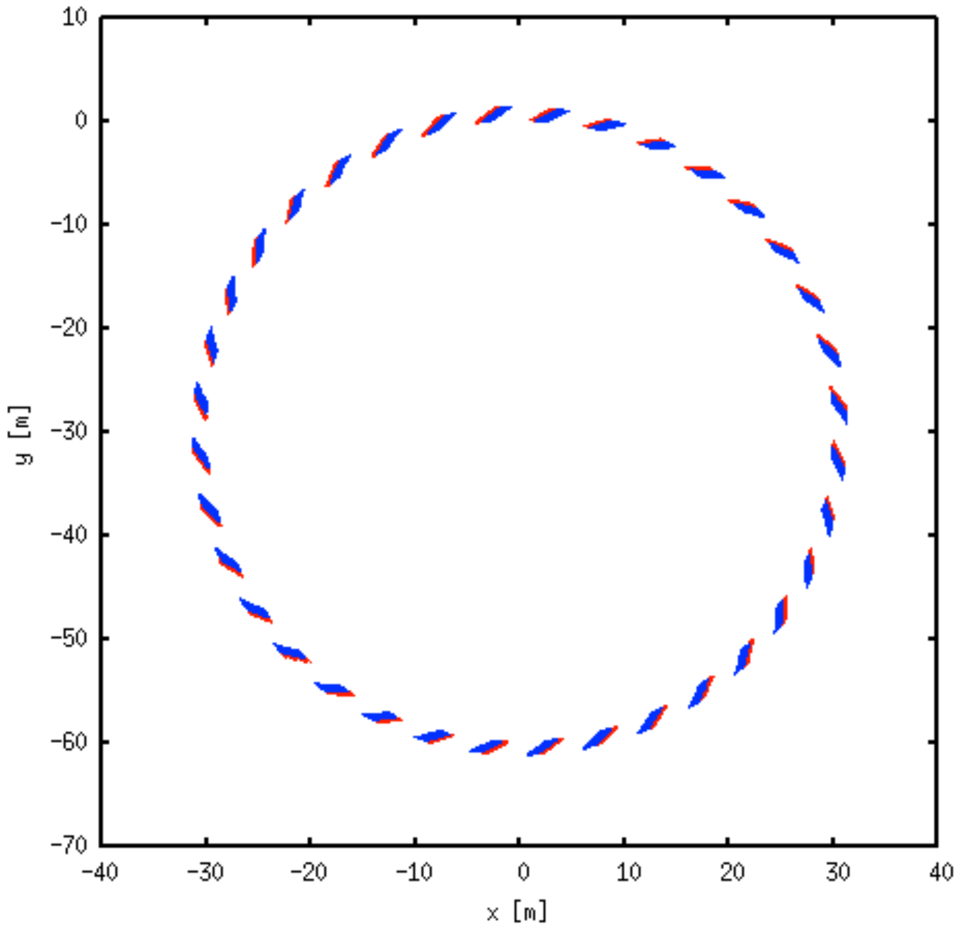
Parameter search (3)

Type	DF-Spiral
Kinetic energy	0.4 - 3 GeV
Pex/Pin	~ 4
Cell number	36
Packing factor	0.31
Spiral angle	58
Field index	50
Orbit excursion	0.82 m
Rex/Rin	31.0 / 30.2 m
Bmax@orbit	3.0 (3.3) T
Straight	3.6 m



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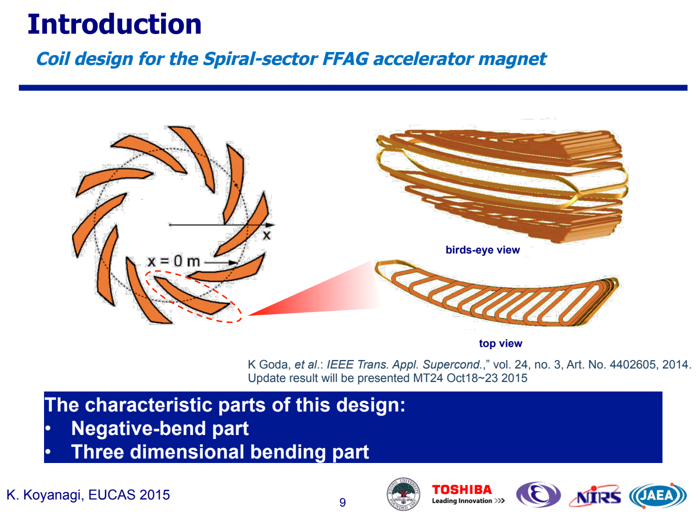
Prospect

10 years plan

10 years R&Ds plan (draft)

- System developments.
  - Gradient magnet design and construction with tuneability of field profile (prototype with a normal conducting magnet).
  - Superferric magnet design and construction with a cryocooler refrigerator.
  - Broadband RF cavity.
  - Diagnostics with wide aperture vacuum chamber.
  - etc.



Superferric magnets R&D in Japan

- Optics design and dynamics study.
  - Injection (and extraction) optics.
  - Design of collimation.
  - Beam stacking experiment.
  - Four fold symmetry with long straight sections.
  - Establish necessary and sufficient knobs for user operation.
  - Effects of the finite dispersion function at RF cavity.
  - Beamloading and its compensation.
  - Higher order resonance and dynamic aperture.
  - Impedance calculation and suppression of instabilities.
  - etc.

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Summary

- Ultimate circular accelerators should minimise electricity for the lattice magnets.
  - DC operation with superconducting magnets or permanent magnets.
- Linear and circular accelerators do not make any difference in terms of energy efficiency when the most of electricity goes into the RF cavities.
  - Is this true statement?
- Fixed Field Alternating Gradient (FFAG) accelerators have several advantages.
  - Use DC magnets and energy can be over 1 GeV (advantage against cyclotron).
  - Time structure of output beam can be controlled because it is like a linac and storage ring together (advantage against linac).
  - But needs R&Ds and demonstration.
- FFAG optimised as a few GeV proton driver is discussed.
  - Combination of conventional spiral and radial sector machines.
- We are making a 10 years R&D plan right now.
  - To be recognised as a member of accelerators for user operations.

Thank you for your attention.