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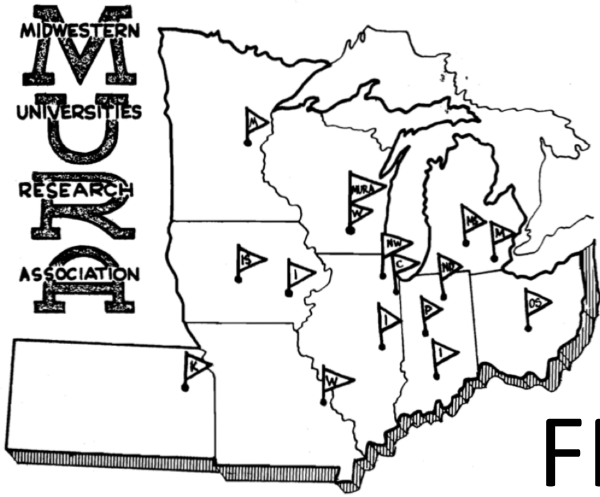


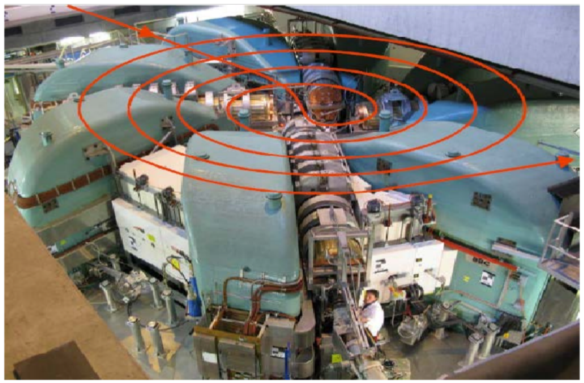
FFA Renaissance

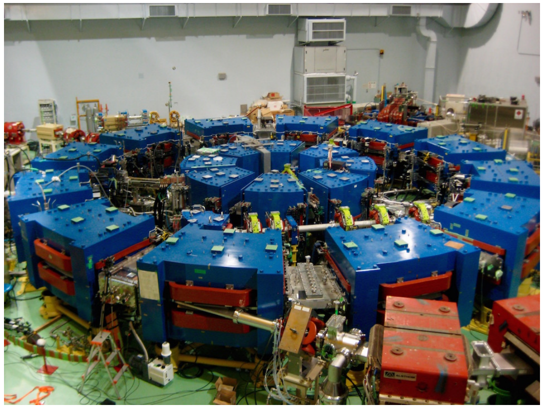
REPORT ON A VISIT TO HARWELL, ENGLAND

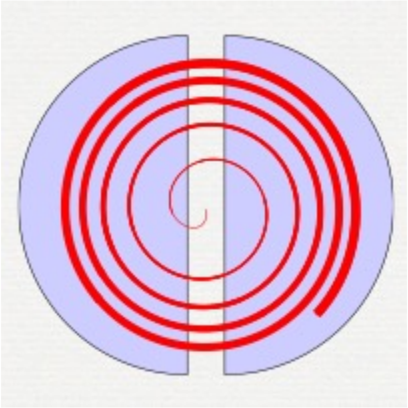
D. J. Kelliher
STFC Rutherford Appleton Laboratory

Zgoubi Workshop 2019, Boulder, CO

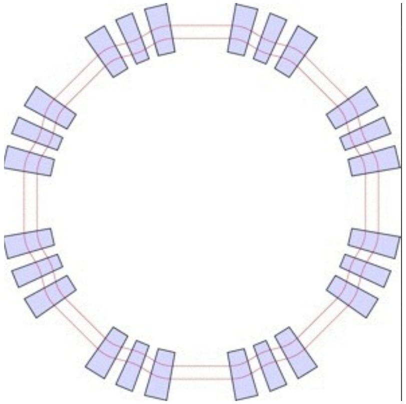
Circulating particle accelerators



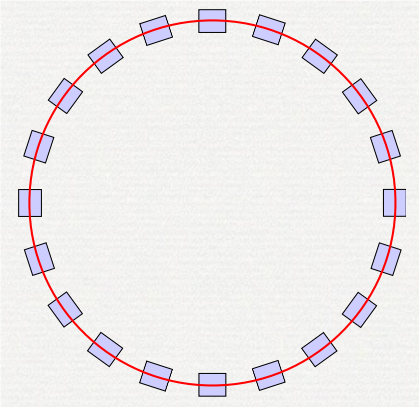




Cyclotron



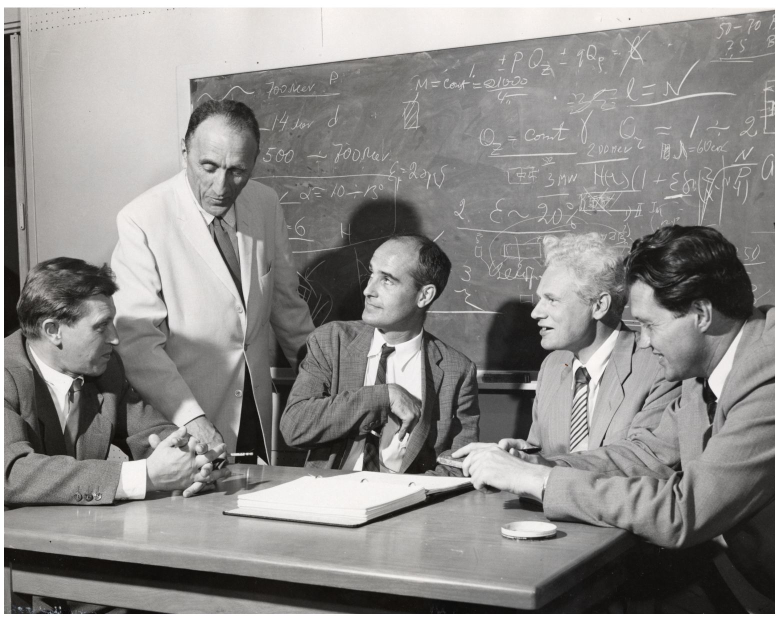
FFA



Synchrotron

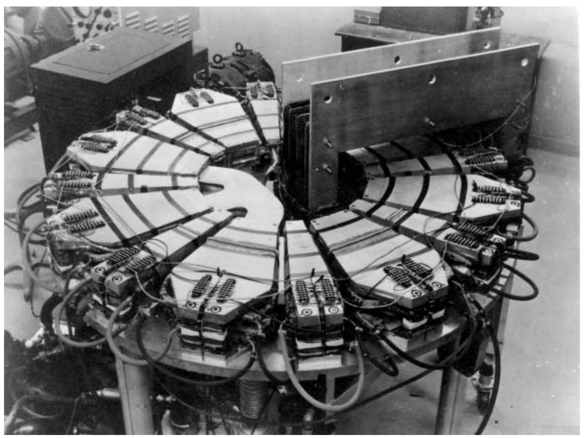
Fixed Field alternating gradient Accelerator (FFA)

- FFAs combine the advantages of a fixed magnetic field (high repetition) with those of an alternating gradient (smaller magnet apertures).
- The idea was independently developed by Kolomensky, Okhawa and Symon shortly after Courant and Snyder's AG focusing paper.

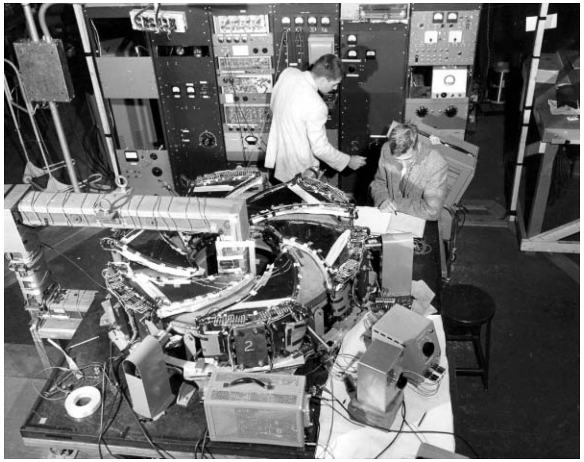


MURA (1954 – 1967)

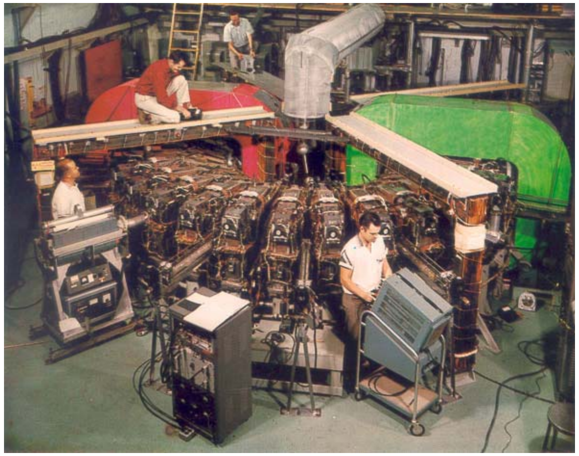
(Midwestern Universities Research Association)



400 keV radial sector FFA



Spiral sector FFA



50 MeV radial sector FFA

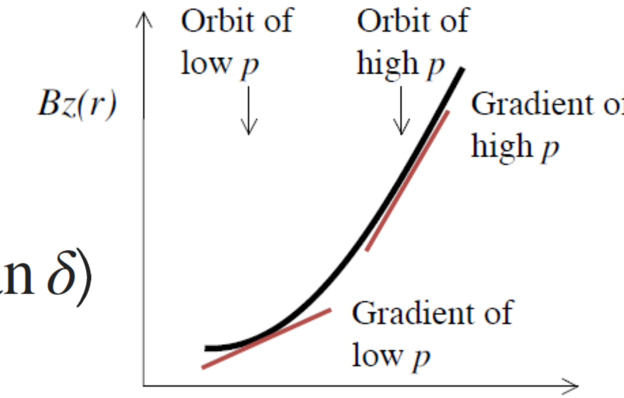
- A number of electron models were commissioned.
- Numerous innovations in accelerator physics were developed at MURA.
- A 30 MeV ”ring phasotron” was constructed at the Lebedev Physical Institute, USSR.

Scaling FFAs

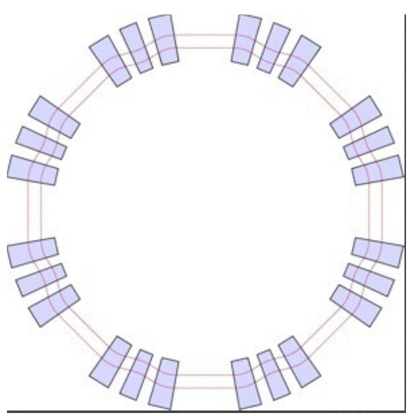
- In scaling FFAs, in order to keep the tune constant with momentum, the field profile has the following form

$$B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k \cdot F\left(\theta - \tan\varsigma \ln\frac{r}{r_0}\right)$$

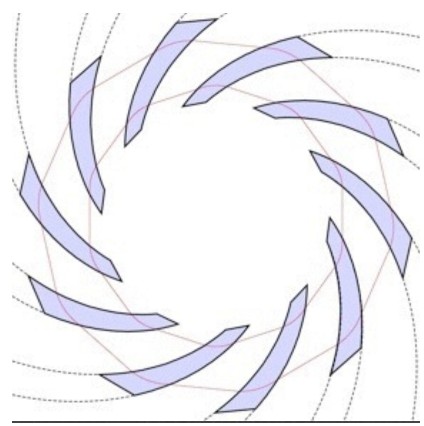
$$Q_x^2 \approx 1 + k \qquad Q_y^2 \approx -k + F^2(1 + 2\tan\delta)$$



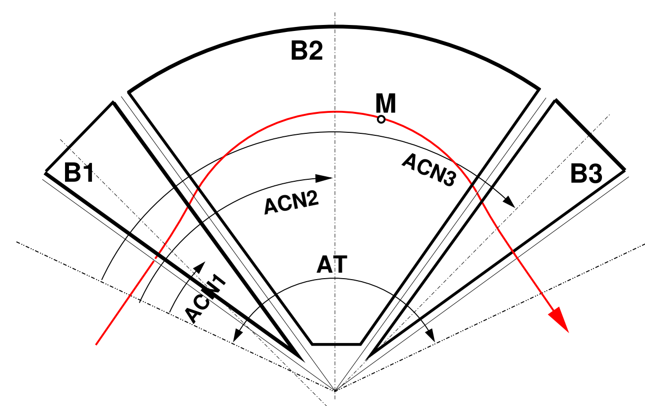
$$K_x = \frac{1}{p}\frac{\delta B_z}{\delta r}$$



Radial sector, ζ= 0, reverse bends



Spiral sector, ζ= constant.

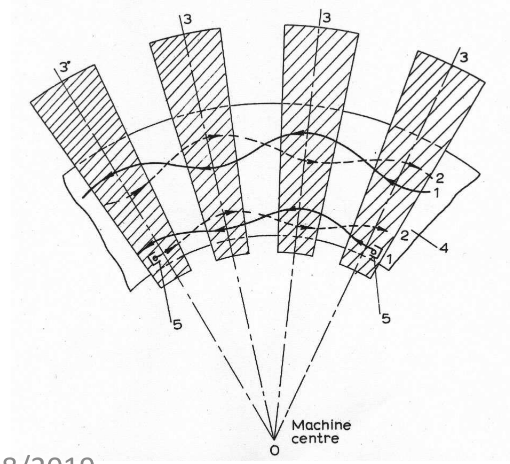


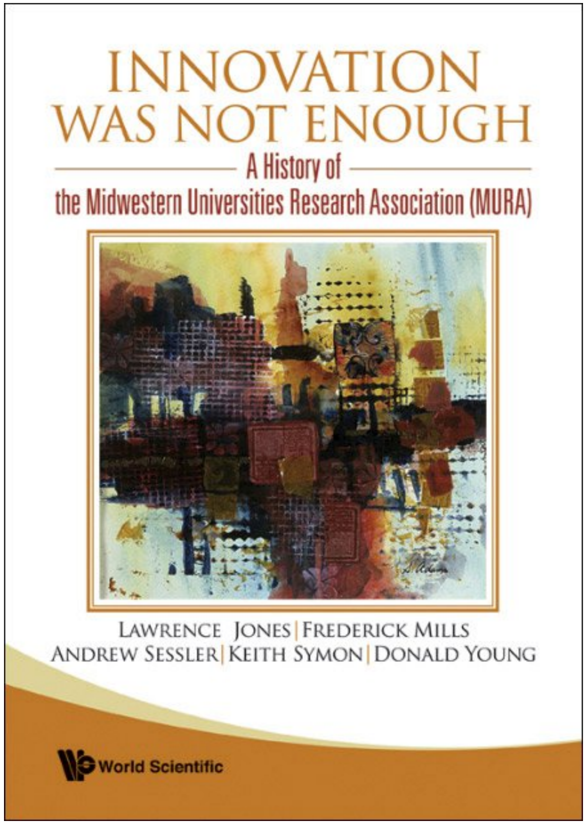
DFD triplet

MURA legacy

(i) beam stacking,
(ii) Hamiltonian theory of longitudinal motion,
(iii) useful colliding beams (the idea itself is quite old),
(iv) storage rings (independently invented by O'Neill),
(v) spiral-sector geometry used in isochronous cyclotrons,
(vi) lattices with zero-dispersion and low-β sections for colliding beams,
(vii) multiturn injection into a strong-focusing lattice,
(viii) first calculations of the effects of nonlinear forces in accelerators,
(ix) first space-charge calculations including effects of the beam surroundings,
(x) first experimental measurement of space-charge effects,
(xi) theory of negative-mass and other collective instabilities and correction systems
(xii) the use of digital computation in design of orbits, magnets, and rf structures,
(xiii) proof of the existence of chaos in digital computation, and
(xiv) synchrotron-radiation rings

F. T. Cole, "O Camelot! – A Memoir of the MURA years"

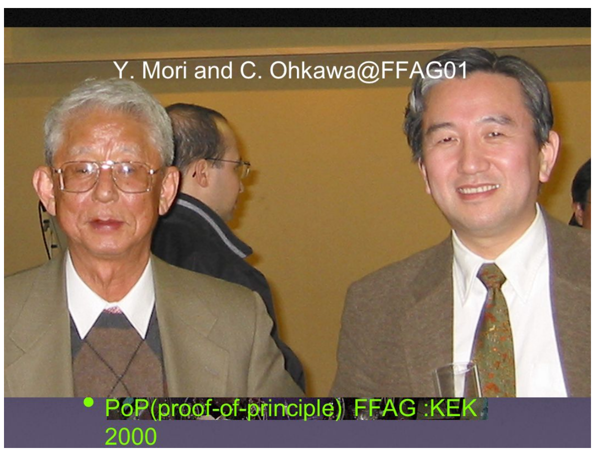


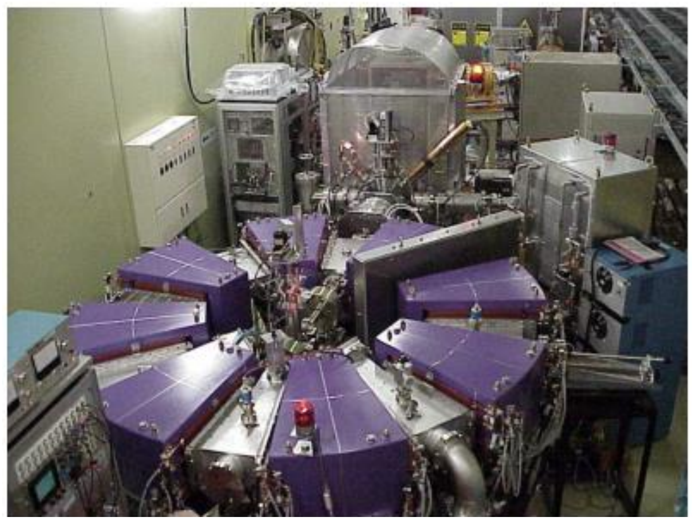


MURA report archive:
http://lss.fnal.gov/archive/other/mura/

Rebirth in Japan

- Development of magnetic alloy (MA) RF cavity allowed the frequency variation required by scaling FFAs.
- Improvement in magnet design tools allowed the nonlinear field profile to be realised.





Parameter list

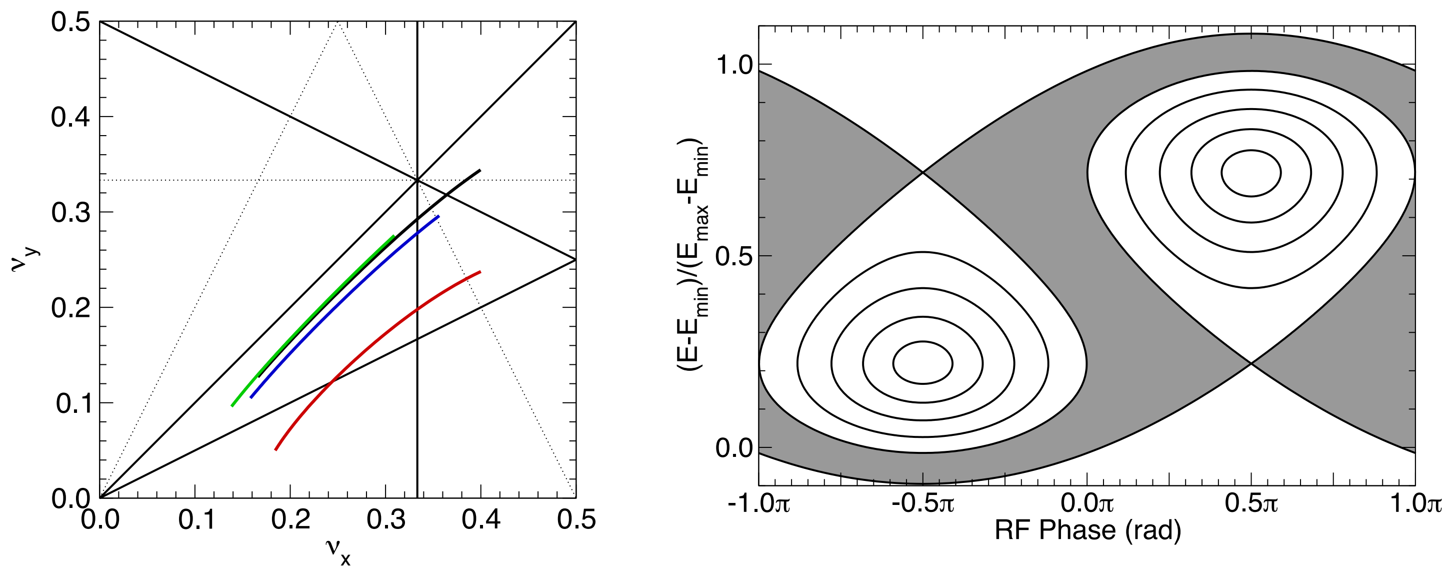
sector number	8 (DFD triplet)
k value	2.5
kinetic energy	50-500keV
fmagnetic field	0.14-0.32T(F)
	0.04-0.13T(D)
average radius	0.81-1.14m
betatron tune	2.22-2.16(Hor.)
	1.26-1.23(Ver.)
revolution freq.	0.61-1.40MHz
RF voltage	5kVpp

PoP radial sector scaling FFA (1999)

Linear non-scaling FFA

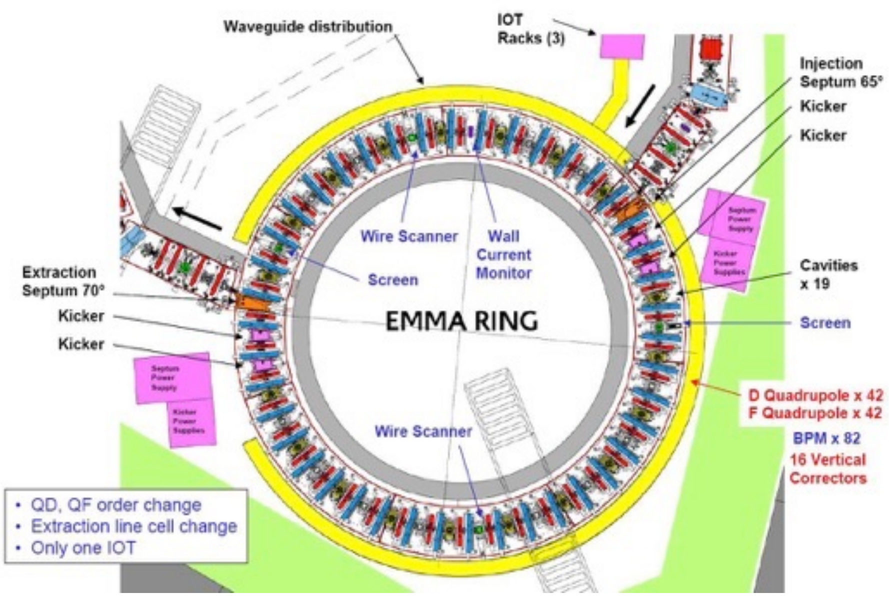
- The magnetic field is linear i.e. dipoles/quadrupoles only.
- The magnets are typically compact.
- The tune will decreases with momentum and pass through many resonances. Accelerate rapidly to survive!
- Use of the “serpentine channel” enables rapid acceleration through the resonances.

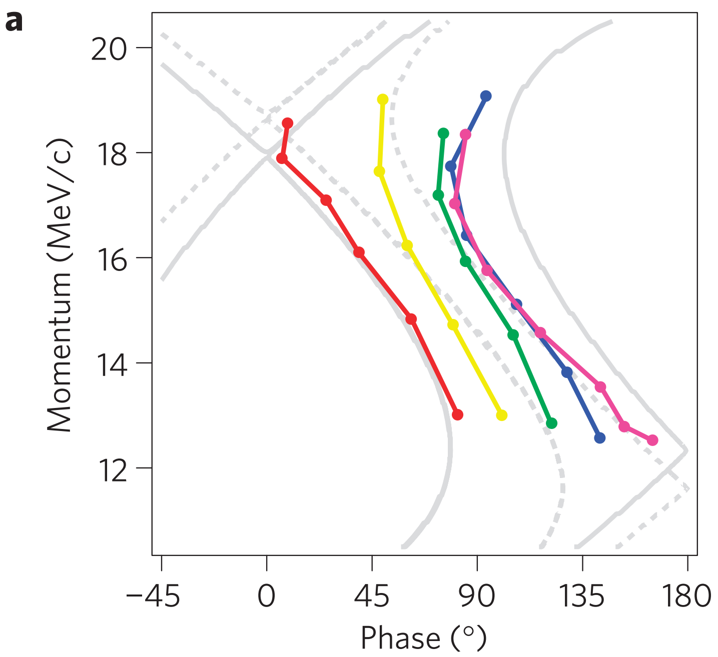
J. S. Berg (2008)



Left: 25 GeV Neutrino Factory accelerator chain featuring a linear NS-FFA. Right: tune diagram.

EMMA (Electron Model for Many Applications)





- EMMA is a linear, non-scaling FFA. It is a densely packed ring consisting of 84 quadrupoles (offset to get bending).
- Experiments demonstrated that the beam is accelerated through integer tunes in the so-called serpentine channel without significant growth in oscillation amplitude.

Potential applications

High Rep Rate	High power applications	Neutron spallation driver, ADS
High momentum acceptance		Multi-pass RLA, gantry.
Rapid acceleration	(Linear non-scaling)	Unstable particle accel.

+ Energy efficiency (e.g. use permanent magnets).

Ongoing FFA projects worldwide

Project	Particle	MeV k.e. (	Machine type	Magnet tech	Institution	Timescale (Years)	Cost ($M) v	Status (Con	Application
ATF-FFAG	e	18-70	Linear non-scaling	Permanent	BNL		Very small	Complete	demo of 4x momentum range
MERIT	p	10-12	Scaling	Electromagnet	KURRI	0.5	Medium	Funded	Muon production
35MeV radioisotope	alpha+p	0.05-35	Non-linear non-scaling	Electromagnet	Commercial (US)	2	Medium	Funded	Radioisotopes
CBETA	e	42-150	Linear non-scaling	Permanent	BNL+Cornell	3	Large	Funded	eRHIC model
ATF-VFFAG proto	e	18-70?	Vertical scaling	Permanent	BNL	1	Very small	Future	demo of vffag
Harmonictron proto	e	0.02-0.1	Vertical scaling w/harmo	Electromagnet	KURRI	1	Very small	Future	demo of vffag+hnj and CW protons
Dejan's gantry	p	30-250	Linear non-scaling	Permanent	DoE/BNL	2	Small	Future	Proton cancer therapy
Ion therapy	ions	250-400	Scaling or NLNS	?	Universities(US)+I	5	?	Future	Ion cancer therapy
Microtron FFAG	C6++p	6-60	Non-linear non-scaling	Superconducting	Columbia U.	5	Medium	Future	Radiobiology
ADSR	p	400	Scaling	Electromagnet	KURRI	5	Medium	Future	Accelerator-driven subcritical reactor
CBETA phase 2	e	>=150	Linear non-scaling	Permanent	BNL+Cornell+(Da	6	Large	Future	X-rays, electron expts.
NIMROD3 proto	p	3-40	Spiral scaling	Electromagnet	RAL	10	Large	Future	Model of ISIS upgrade
NORMA	p	30-350	Scaling racetrack	Electromagnet	Manchester U.	?	?	Future	Proton therapy and tomography
At least 2 commercial FFAG projects not included on this list									
Component development					**Institution**			**Status (Con**	**Application**
DF spiral magnet					RAL			Funding lik	NIMROD3
Superconducting magnet for spiral scaling FFAG					Kyoto U.+KEK+Toshiba			Complete (but not published)	
eRHIC linac-ring optior	e	1300-212(	Linear non-scaling	Permanent	DOE/Electron Ene	3		DOE Funde	eRHIC model

Cost categories	
Very small	Zero up to $100k
Small	up to $1M
Medium	up to $10M
Large	over $10M
Costs very roughly including labour but not lab overhead	

S. Brooks, FFA17 workshop, Cornell

In the past few years

- CBETA ERL.

  CBETA Design report, arXiv:1706.04245

- Beam physics measurements.

  S. L. Sheehy et al, PTEP (2016)

- Combine the radial and spiral FFAs (DF-spiral).

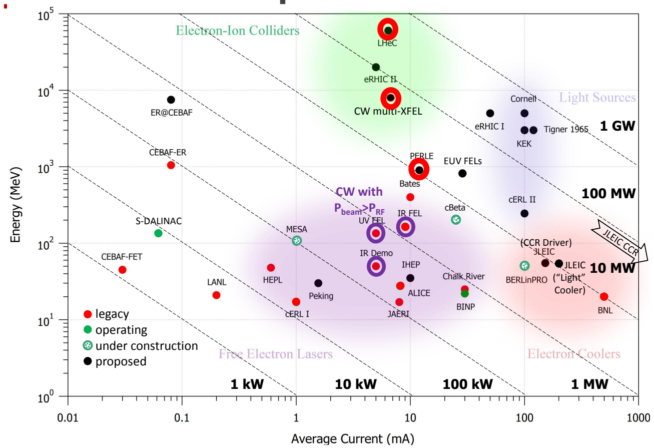
  S. Machida PRL 119, 064802 (2017)

- Vertical FFA.

  S. Brooks PRAB 16, 084001 (2013)

CBETA ERL (Talk on Wednesday)

The ERL Landscape: The State of the Art



David Douglas, PERLE collab meeting (2018).

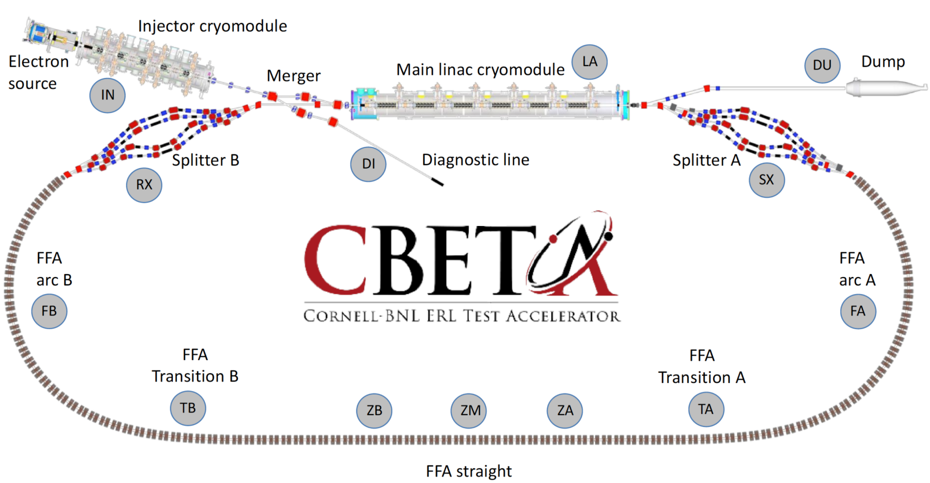
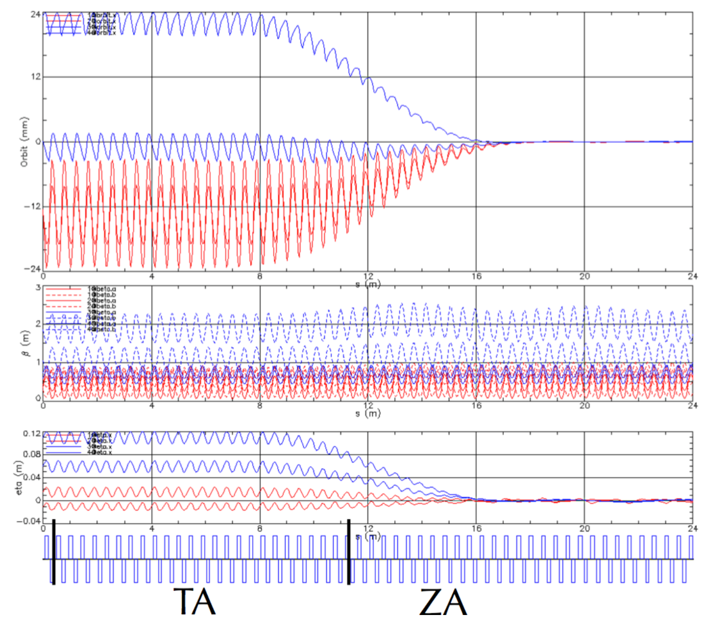


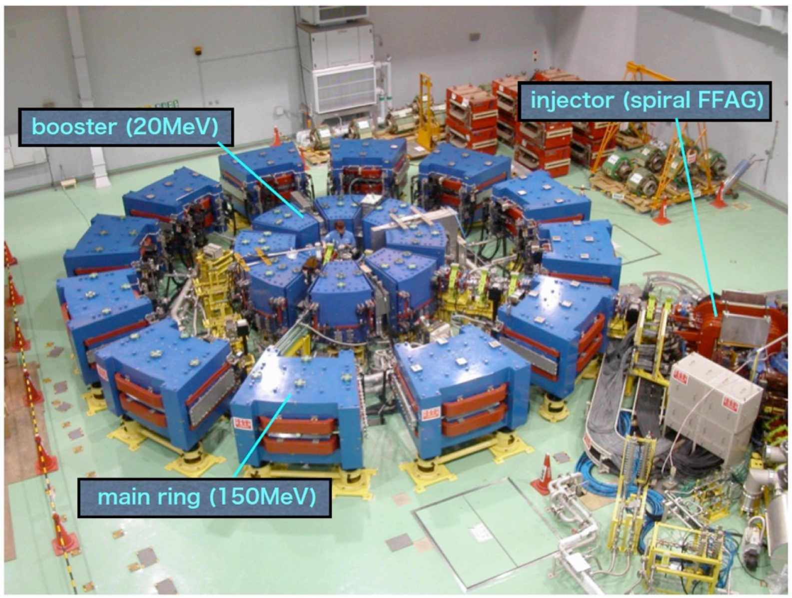
Figure 0.1.1: The CBETA machine layout.

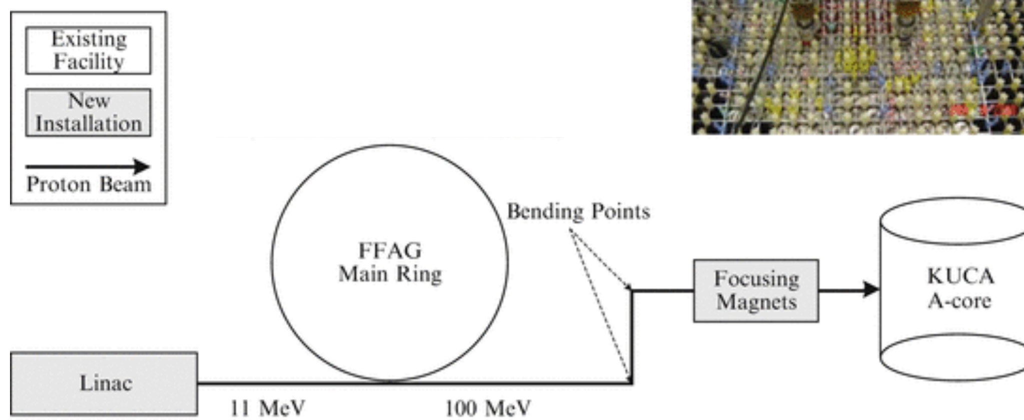


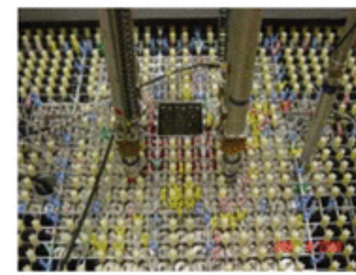
Adiabatic transition

KURNS (KURRI), Osaka

150 MeV proton FFA at KURNS, Osaka





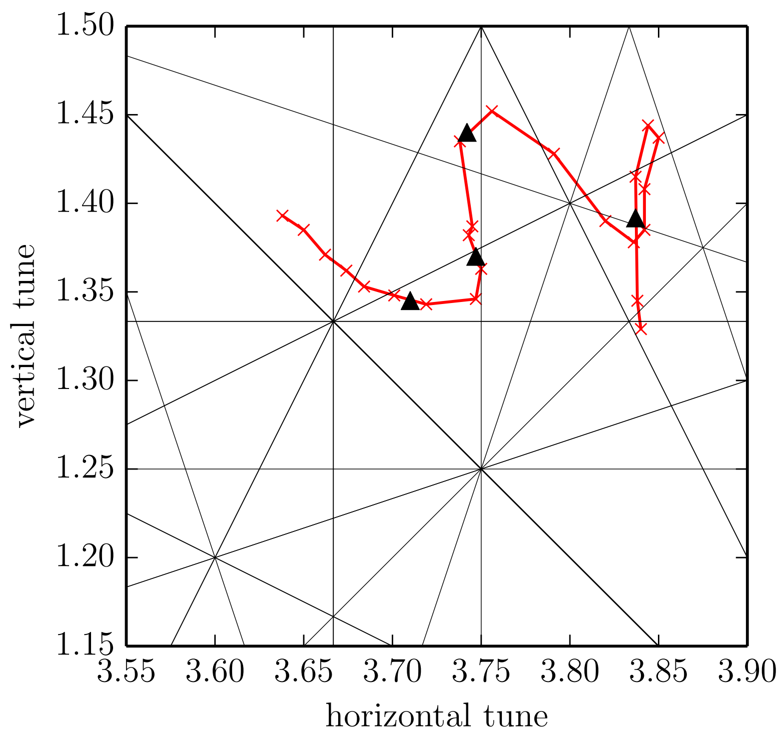


- The protons extracted from the FFA are transported to a tungsten target in a subcritical reactor core.
- Investigate change of criticality with neutron flux.

KURRI collaboration:
Summary of measurements

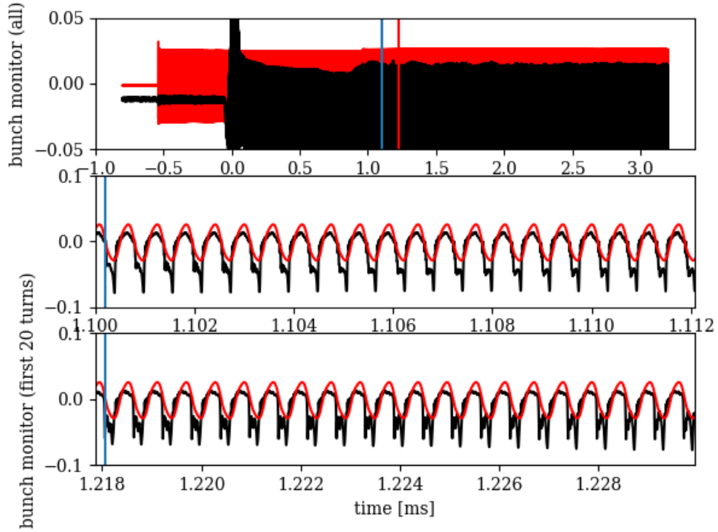
Measurement	Result/Utility
Radial position vs time	Field index, Dispersion, COD
Vertical coherent oscillations	Vertical orbit matching
Betatron tunes	Tune excursion
Dispersion at foil	Dispersion matching
Synchronous phase vs rf voltage	Foil thickness

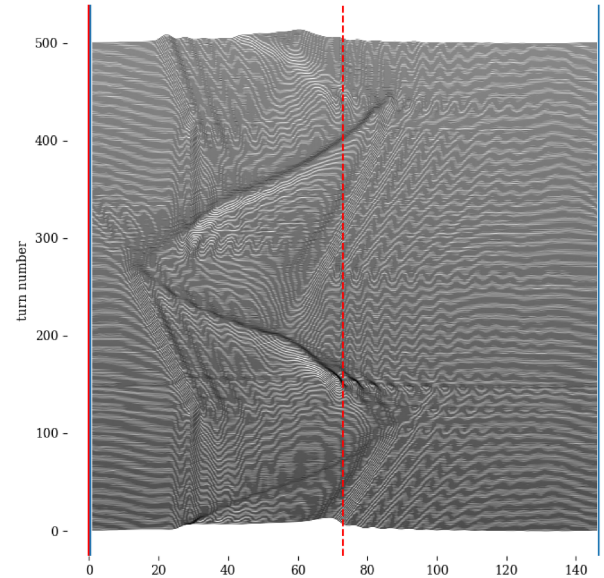
S. L. Sheehy et al, PTEP (2016)

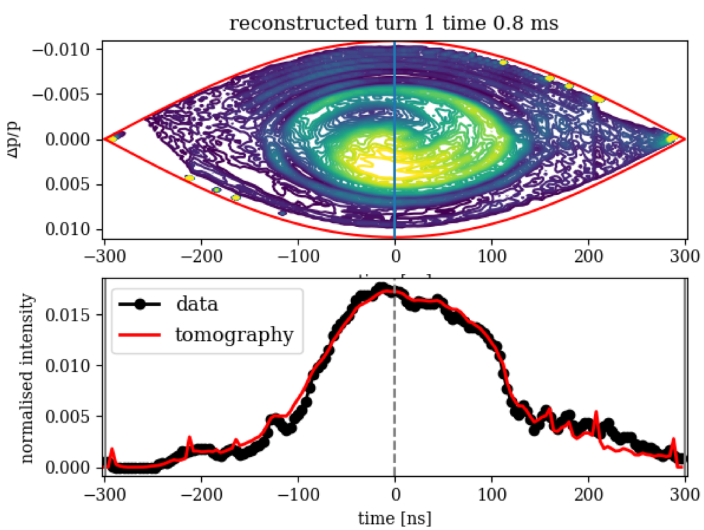


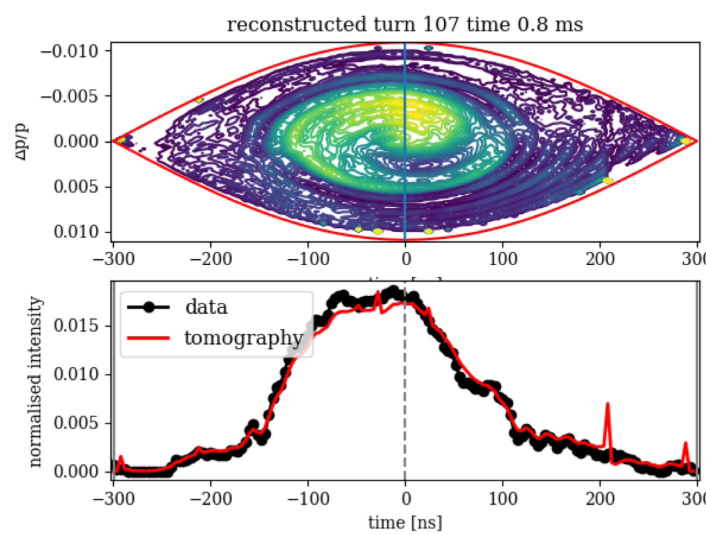
Tune variation over momentum range

Longitudinal tomography (2018)

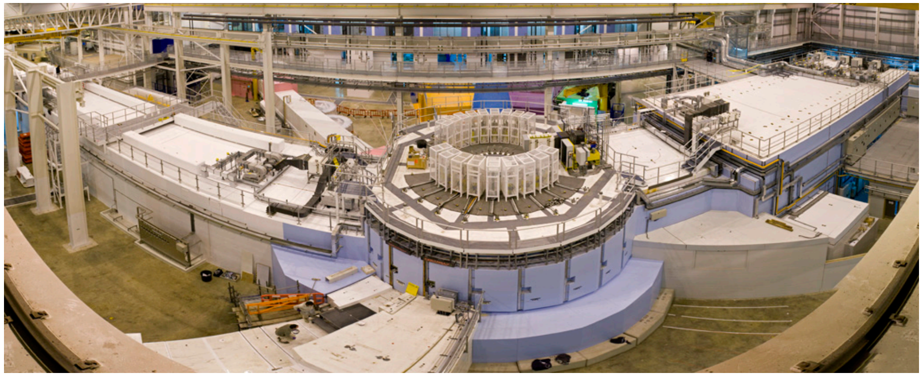








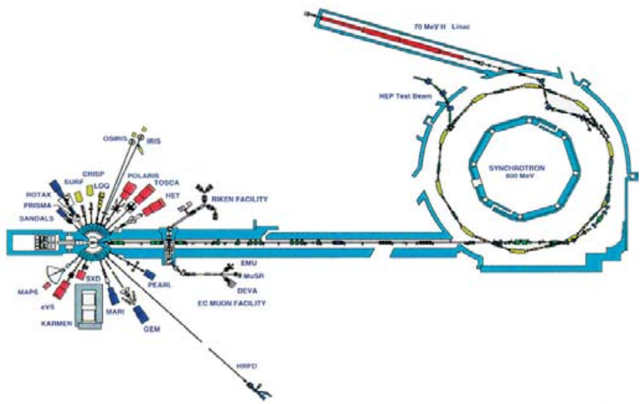
D. Kelliher et al, IPAC19



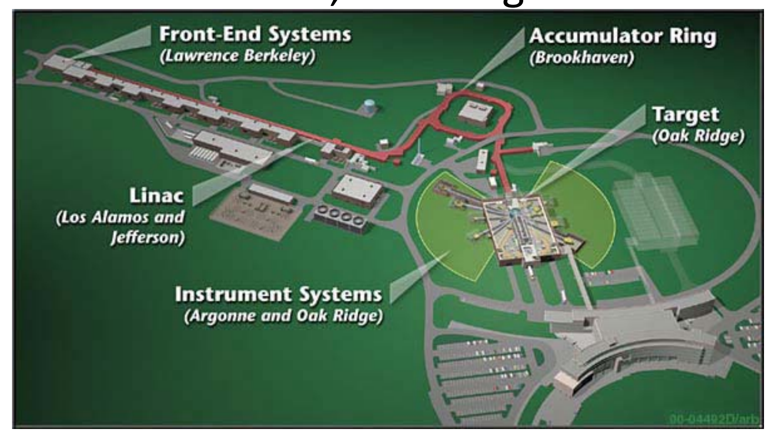
ISIS, RAL, Oxfordshire

Spallation sources

ISIS, RAL



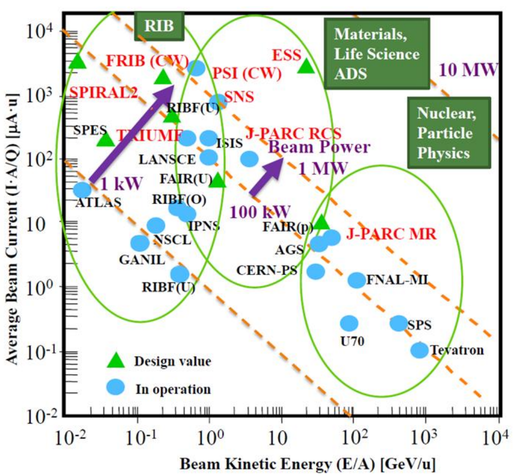
SNS, Oak Ridge

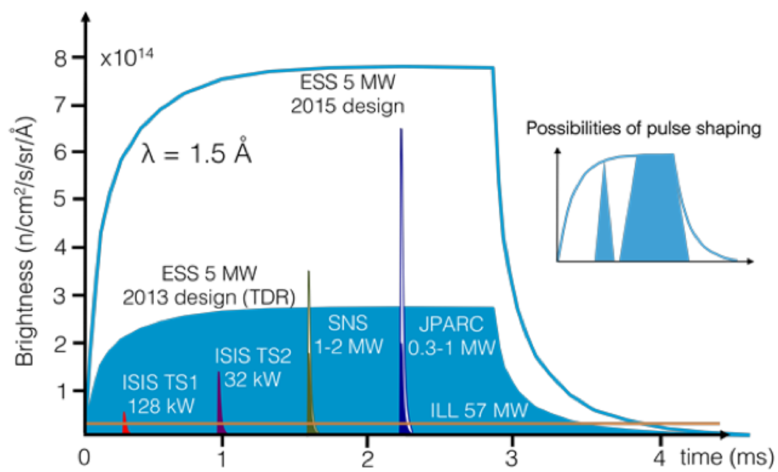


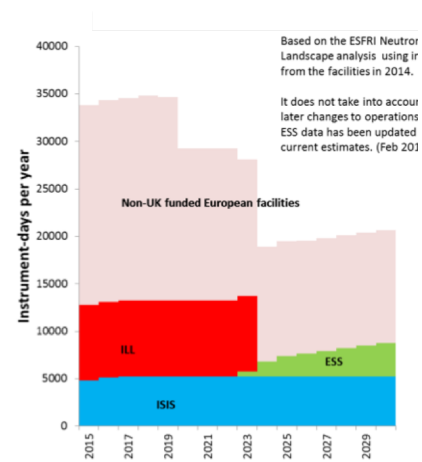
Quantity	Continuous	Long-pulse	Short-pulse
Facilities	PSI-SINQ	ESS	SNS,JPARC,CSNS, ISIS, Lujan
target	Watercooled, lead-filled zircalloy tubes	Helium cooled, rotating tungsten wheel	Liquid mercury, water-cooled tungsten plate
power	1.3 MW	5 MW	1.4/1/0.2/0.16/0.1 MW
proton energy	590 MeV	2.5 GeV	1.0/3.0/1.6/0.8/0.8 GeV
pulse length	continuous	2.6 ms	< 1 µs
Repetition rate	-	14 Hz	60/25/25/50/20

Adapted from F.X. Gallmeier (2016)

The case for a new ring-based spallation neutron/muon source







"Now is the right time to be thinking about an ISIS facility upgrade which would be complementary to ESS and provide enchanced neutron capacity in Europe beyond 2030" – ISIS-II working group report

A new FFA concept – the DF-spiral

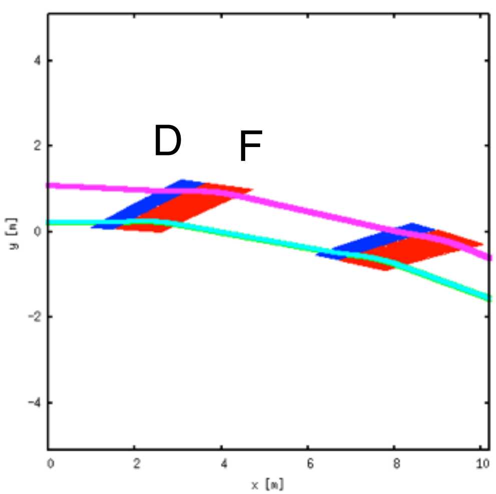
- Radial sector machines feature reverse bend magnets in order to increase magnetic flutter F. Spiral sector have no reverse bends. However, the spiral angle increases with number of cells making the magnet challenging to construct.
- To reduce the required spiral angle, introduce a negative field region at one edge of the spiral magnet. The F/D ratio can be adjusted, so the lattice is tuneable. This is the so-called DF-Spiral FFA (S. Machida).

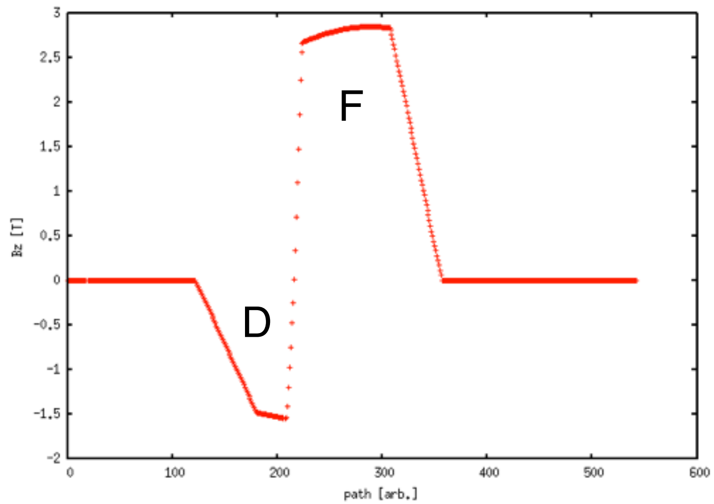
$$Q_x^2 \approx 1 + k \qquad Q_y^2 \approx -k + F^2(1 + 2\tan\delta)$$

where

$F^2 = \left\langle (B - B_{av})^2 \right\rangle / B_{av}^2$

δ = edge angle

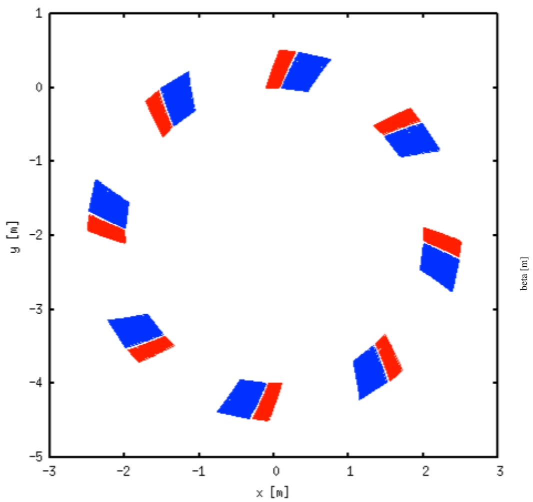


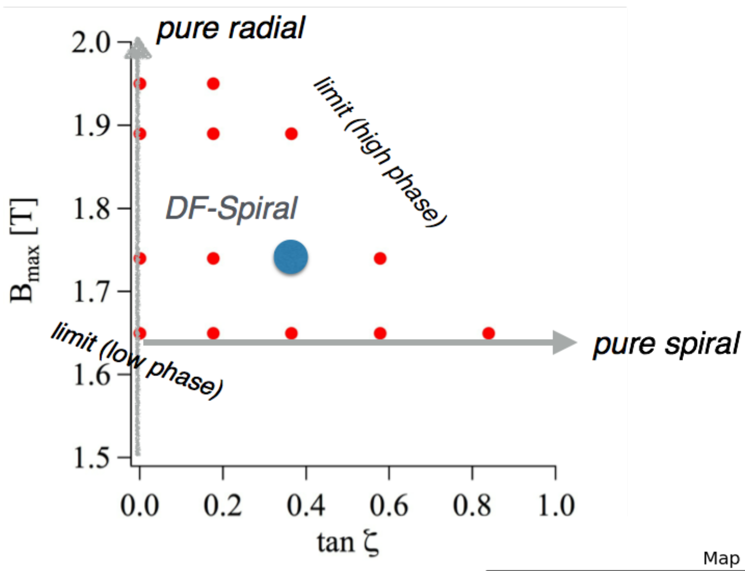


S. Machida PRL 119, 064802 (2017)

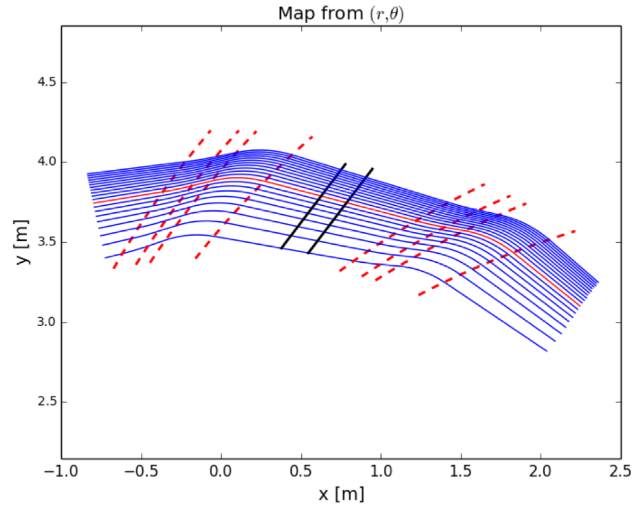
DF-Spiral prototype

S. Machida, FFA15 workshop

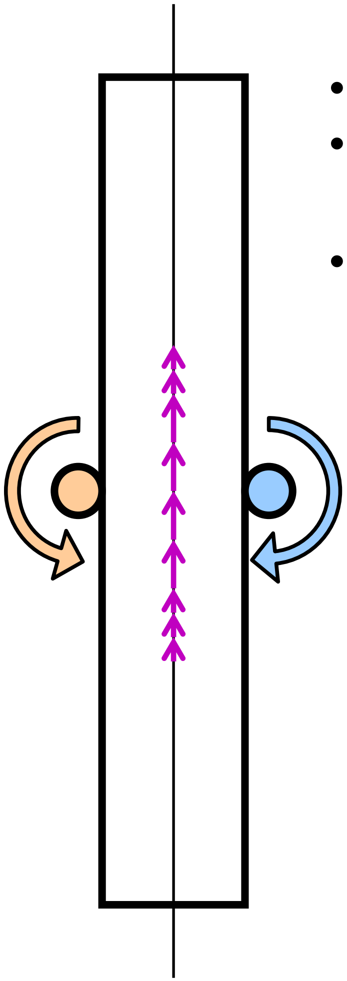




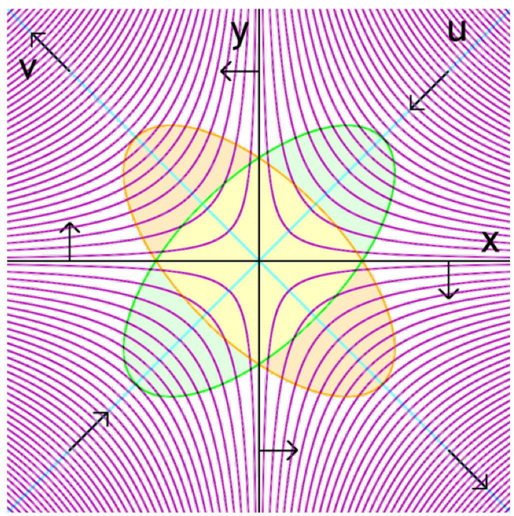
- The FETS DF-Spiral FFA has the following goals
  - Demonstrate DF-Spiral optics and operation.
  - H- injection/extraction.
  - Tunability with additional trim coils.
  - Non-uniform painting at injection.
  - Operation with asymmetric emittance.
  - Beam stacking to shape time structure.



Vertical FFA (S. Brooks)



- Magnetic field increases exponentially in the vertical direction.
- Closed orbits shifted upward/downward and have the same shape at each momentum.
- Ignoring the dipole component, the focusing is that of a skew quadrupole. This means the transverse coordinates are strongly coupled.



For the field in a long magnet with no variation in z, Maxwell's equations in free space reduce to

$$\partial_x B_x + \partial_y B_y = 0, \qquad \partial_x B_y - \partial_y B_x = 0,$$

and B_z constant, assumed here to be zero. The solution to these equations that gives the scaling VFFAG field $B_y = B_0 e^{ky}$ and $B_x = 0$ on the midplane $x = 0$ is

$$B_y = B_0 e^{ky} \cos kx, \qquad B_x = -B_0 e^{ky} \sin kx.$$

Summary

- The FFA field continues to advance driven by novel ideas and technology developments.
- FFAs offer a possible route to high power. At RAL, we plan to build a prototype of such a ring in the next decade.
- FFAs have advantages in energy efficiency, particularly where permanent magnets can be used.