FFAG Projects:
Status, Achievements, and Prospects

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  - scaling FFAGs
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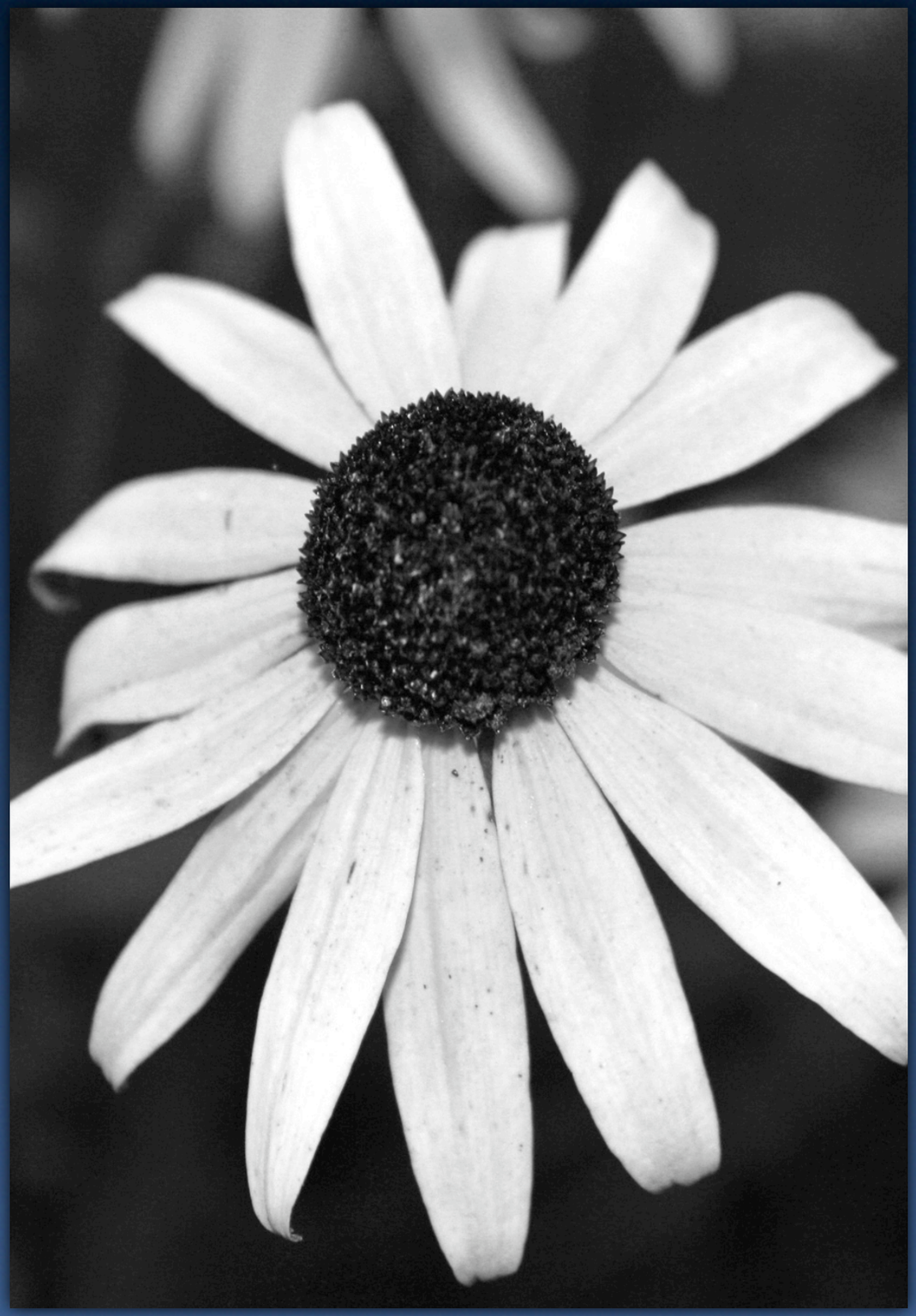


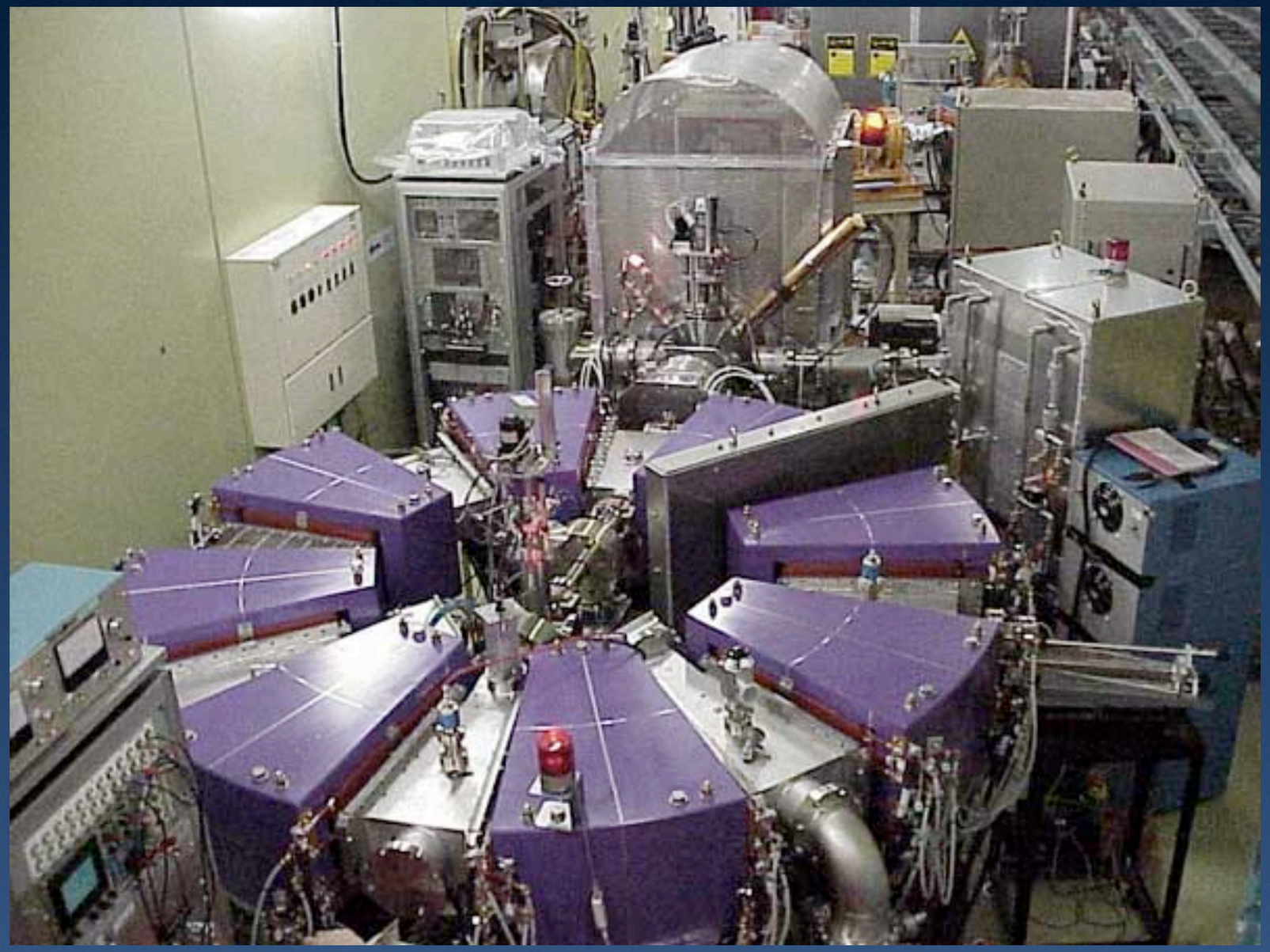
FFAG: Fixed-Field Alternating Gradient

- Constant magnetic field in time
  - Like cyclotron, but non-zero field index
- Strong focusing
  - Like synchrotron
- Moving orbit
  - Like cyclotron, but higher mom. compaction factor
- Advantages
  - Fast acceleration :
    - No needs of synchronization between RF and magnets.
  - High average current with a high rep. rate and modest number of particles in a ring
  - Huge acceptance :
    - transverse (H): > 10000 mm mrad, longitudinal: dp/p > 50%

History of FFAG Accelerator

- Invented in 1950s : Ohkawa, Kerst, Symon
- in 50s-60s : MURA project
  - e-model of radial-sector and spiral-sector designs
  - proton proposal failed because of technical difficulties:
    - complicated magnetic field configuration
    - rf acceleration (thin and high field grad., broadband cavity)
- in 1999 : the first proton FFAG accelerator by Mori's group in KEK
  - 3D field calculation and computer aided tracking
  - rf cavity using magnetic alloy cores

PoP-FFAG, KEK (1999)



- The world's 1st proton FFAG accelerator
- accelerates protons from 50 keV to 500 keV in 1 msec
- without extraction

150MeV-FFAG, KEK (2003)

- a prototype FFAG for proton therapy and accelerator-driven reactor, which can accelerate protons to 150MeV.
- 100 Hz operation with 90% extraction efficiency

Types of FFAG

- Scaling FFAG (MURA, FFAGs in Japan ...)
  - beam dynamics dose not depends on the energy
  - zero-chromaticity (constant tune)
  - with non-linear magnetic field : $$B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k f\left(\theta - \varsigma \ln \frac{r}{r_0}\right)$$
- Non-scaling FFAG (newly invented in 1997)
  - beam dynamics depends on the energy
    - needs to solve problems from the resonance crossing
  - linear field or non-linear field
  - a lot of variations in lattice design
    - would be a more compact lattice then scaling-FFAG
    - isochronous FFAG

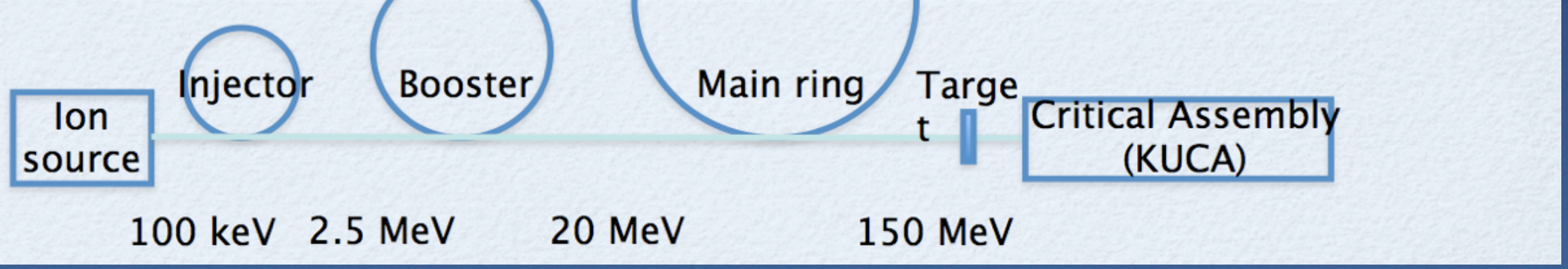
Scaling FFAG

Scaling FFAGs operating or under construction

	Site	Ion	E_{max} (MeV)	Sector type	Cell	Radius (m)	First Beam	Acc. Scheme	Comments
PoP	KEK	p	1	Radial	8	0.8-1-1	2000	rf	The 1st proton FFAG. Accelerate protons from 50 keV to 500 keV in 1 msec.
150MeV	KEK	p	150	Radial	12	4.5-5.2	2003	rf	100 Hz, 90% extraction
ADSR-Injector	KURRI	p	2.5	Spiral (40°)	8	0.6-1.0	2006	induction	Initial spec : 120 Hz, 1 μA Later : 1 kHz, 100 μA, 200 MeV
ADSR-Booster			20	Radial	8	1.4-1.7	2006	rf	
ADSR-MR			150	Radial	12	4.5-5.1	2008	rf	
ERIT	KURRI	p	11	Radial	8	2.35	2008	rf	70 mA ionization cooling ring to produce a neutron beam for BNCT
PRISM-demo	Osaka-U.	α	1.0	Radial	6	3.0	2008	rf	Demonstrate phase-rotation for the mu-e conv. experiment (PRISM)
EB-FFAG	NHV Co.	e	0.5	Spiral (30°)	6	0.19-0.44	2008	induction	Prototype of electron FFAG for industrial applications
Radiatron	RadiaBeam Technologies, LLC (US)	e	5	Radial	12	0.3-0.7	(2008)	induction	Prototype of a high power accelerator for industrial applications

FFAGs for ADSR, KURRI

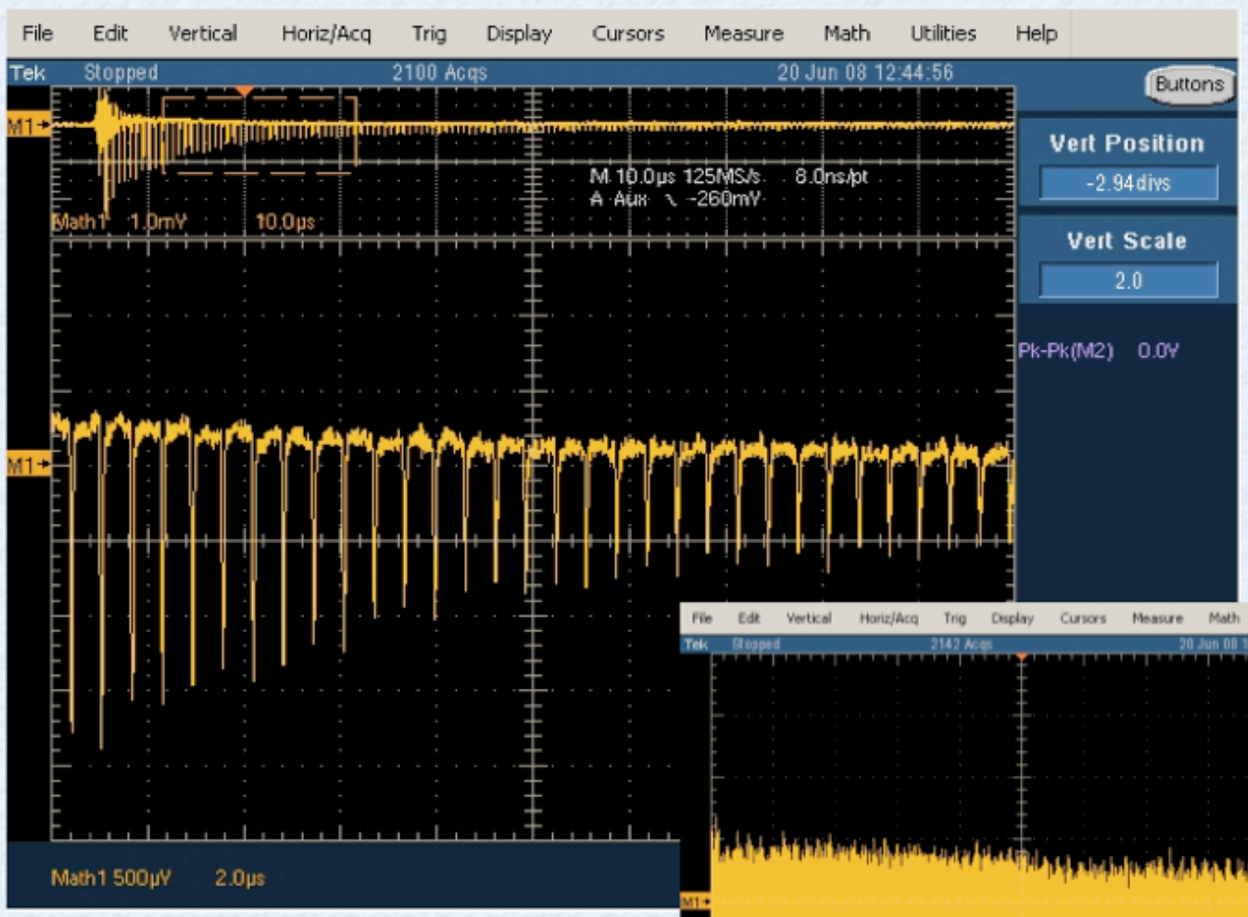
- Purpose of the proejct
  - Basic study for ADSR(Accelerator Driven Sub-critical Reactor) with FFAG accelerator and KUCA(Kyoto University Critical Assembly)



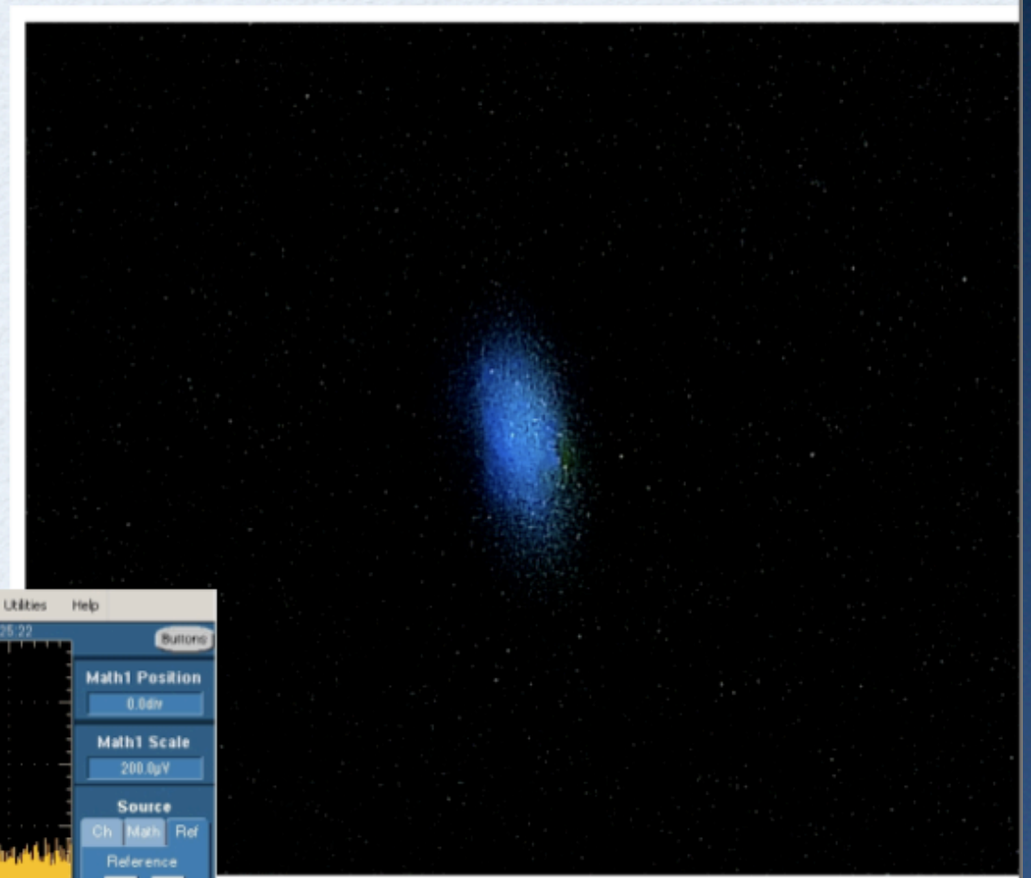
FFAGs for ADSR, KURRI (2008)

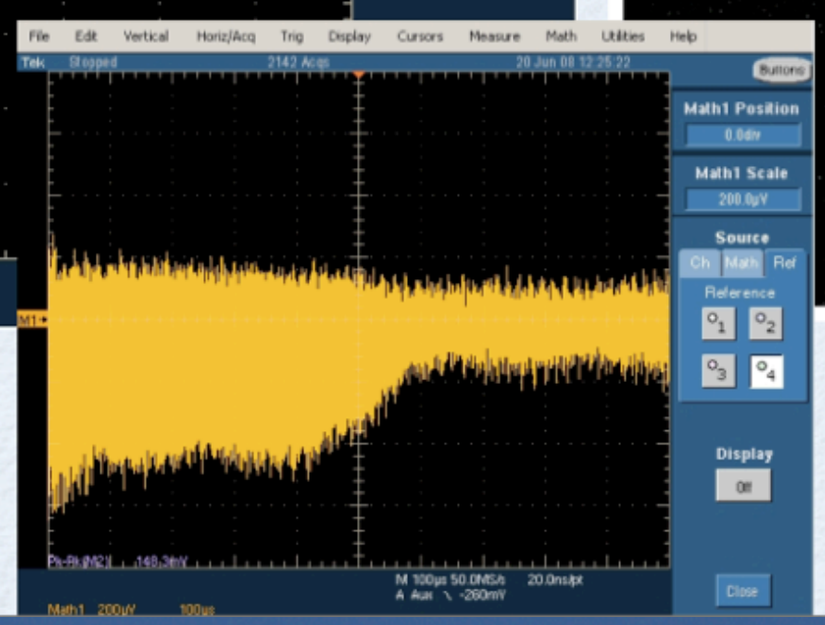
in operation

Injection



100MeV beam





resonance beam loss at ~25MeV

ERIT-FFAG, KURRI

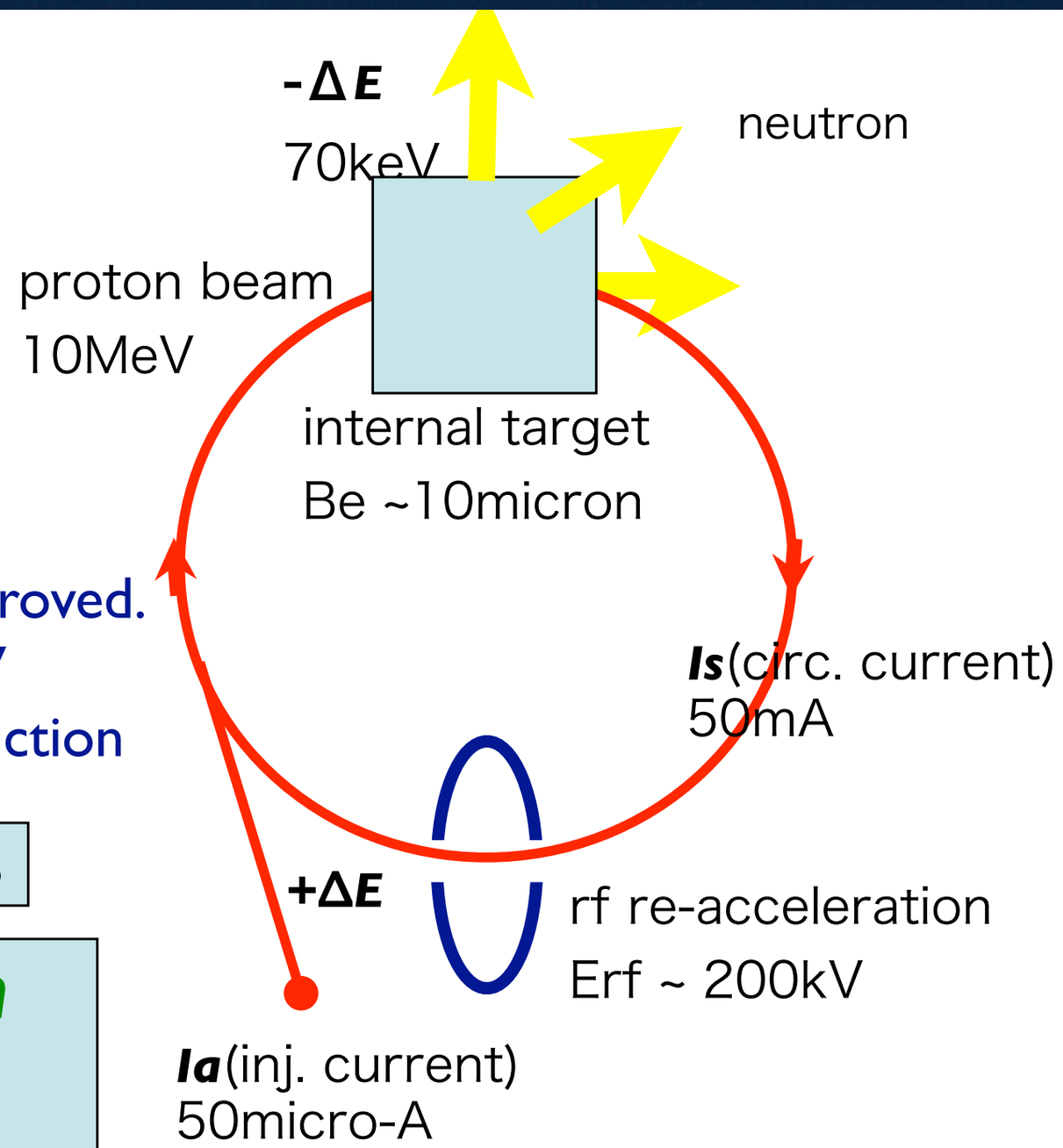
- ERIT : Emittance-energy Recovery Internal Target

- FFAG-ERIT scheme
  - internal target
  - energy loss
    recovered by rf
  - emittance growth
    ionization cooling
  - large acceptance
    FFAG(scaling)
  - target
    heat loss 1-2kW

Project was approved.
2005-2007
Under Construction

Ia=Is/Nt, Nt=1000turns

Need large momentum acceptance! -> FFAG



ERIT-FFAG, KURRI

Injector(RFQ + IHDTL)

Full energy injection

H^- kinetic energy	10 [MeV]
Average beam current	~ 45 [mA]
Repetition	>1 [kHz]

FFAG ring

H^- injection

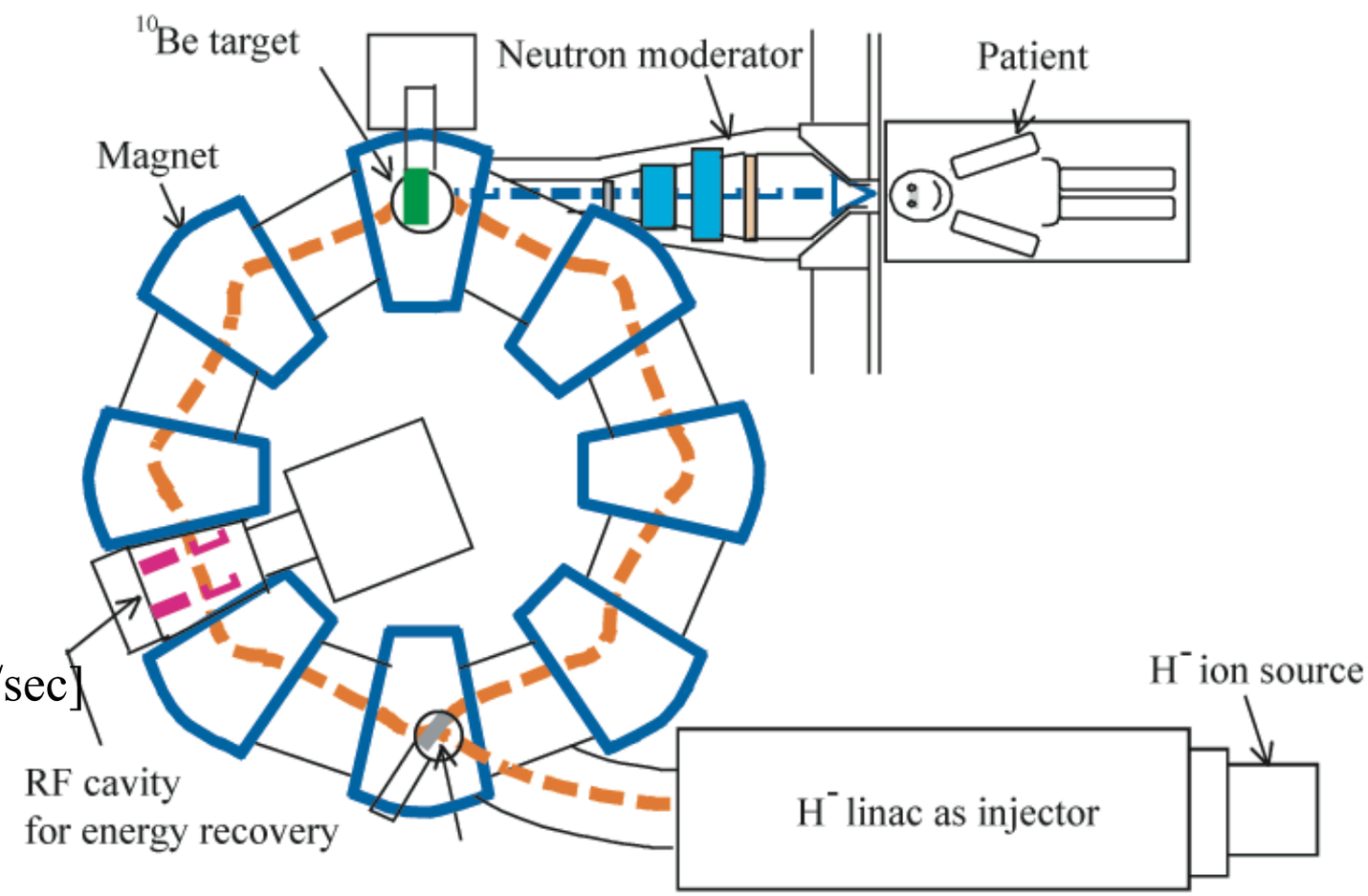
proton kinetic energy	10 [MeV]
Average beam current	~ 45 [mA]

ERIT system

Turn number	> 1000 turn
Internal target thickness	~ 5 [mm]
Neutron beam intensity	> 10^9 [n/cm^2/sec]

RF cavity

RF voltage	> 200 [kV]
Harmonic num.	~ 5

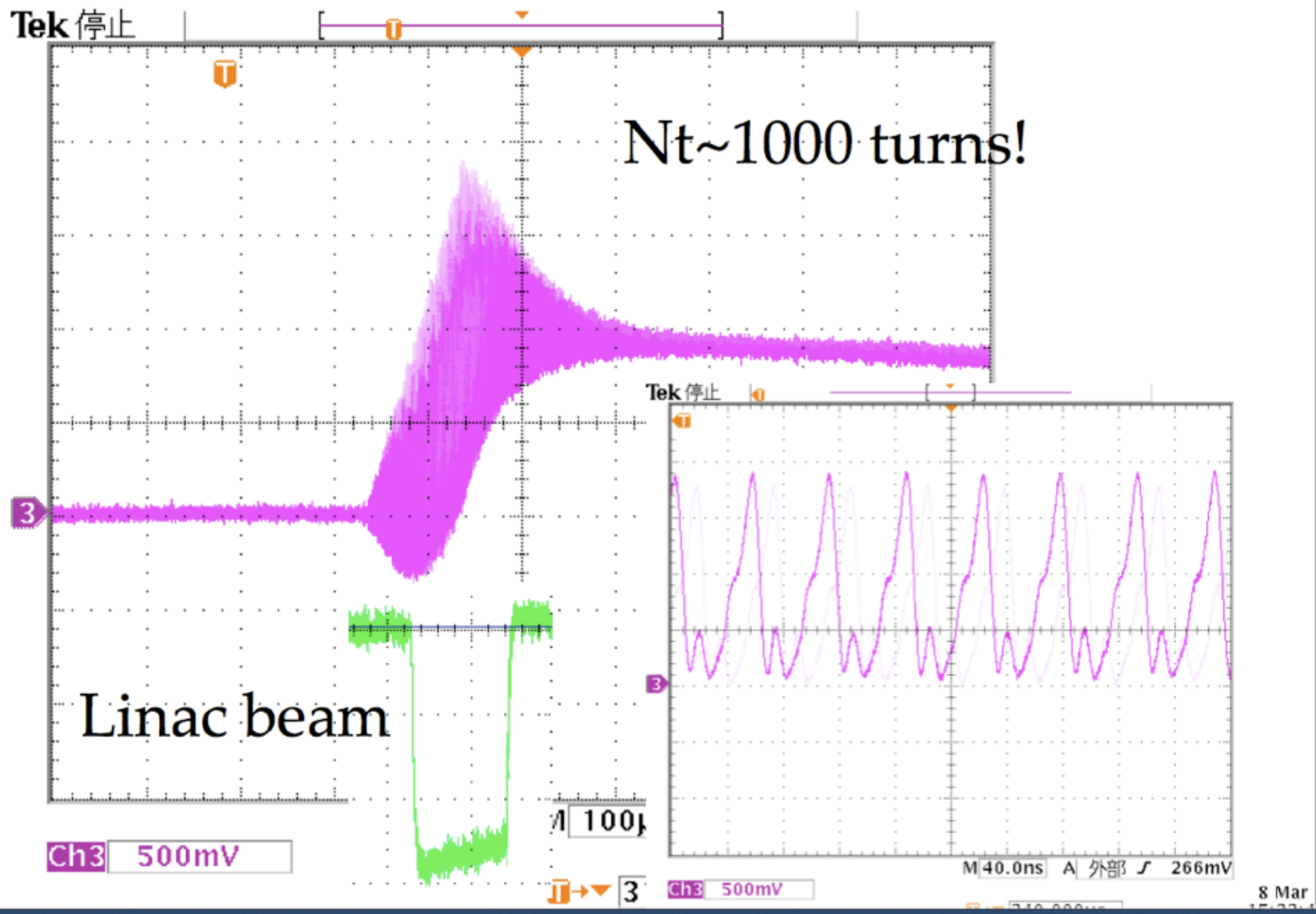


ERIT-FFAG, KURRI

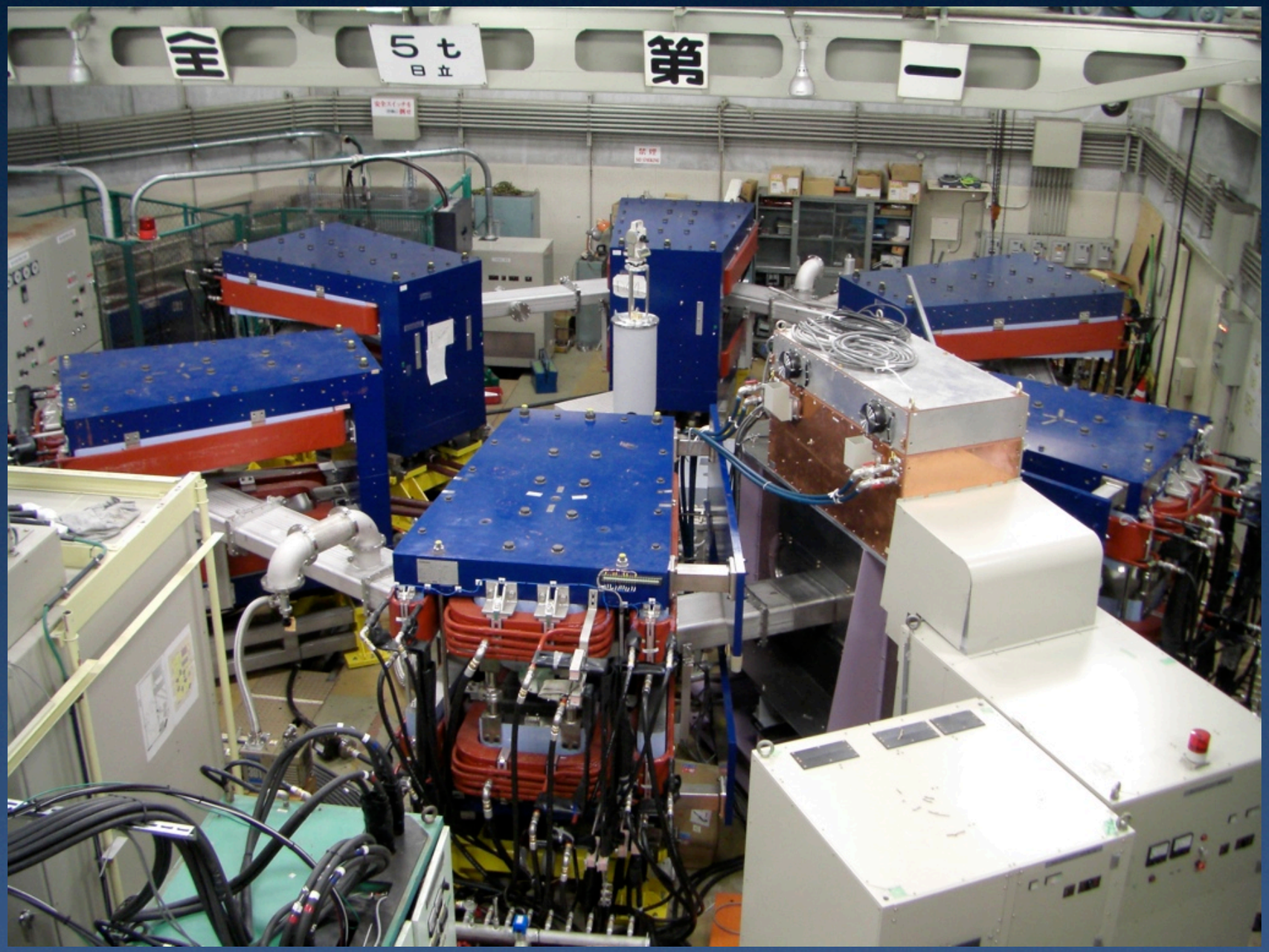
-beam energy	11MeV	-acceptance	Av>3000mm.mrad,
-circ. beam current	70mA		dp/p>+-5%
-beam life(# of turns)	500-1000turns	(full)	

ERIT-FFAG, KURRI (2008) successfully operated

Beam storage



PRISM-FFAG (2008) in operation



- Goal :Build a full-size FFAG-ring for mu-e conv. experiment and test and establish the phase rotation to make monoenergetic beams.

Scaling FFAGs - design studies

	Ion	E_{max} (MeV)	Sector type	Cell	Radius (m)	Rep. Rate (Hz)	Comments
MElCo Laptop	e	1	Spiral (35°)	5	0.023-0.028	1,000	Hybrid, Magnet build
eFFAG	e	10	Spiral (47°)	8	0.26-1.0	5,000	20-100 mA
Ibaraki Med. Acc.	p	230	Spiral (50°)	8	2.2-4.1	20	Proton Therapy, 0.1 μA
LPSC RACCAM	p	180	Spiral (50°)	10	3.2-3.9	>20	p Therapy, One magnet is under construction
MElCo p Therapy	p	230	Radial	3	0-0.7	2,000	SC, quasi-isochronous
MElCo C Therapy	C^{6+}	400	Spiral (64°)	16	7.0-7.5	0.5	Hybrid FFAG/synchrotorons
	C^{4+}	7	Radial	8	1.35-1.8	0.5	
NIRS Ion Therapy	C^{6+}	400	Radial	12	10.1-10.8	200	Compact-radial sector design
	C^{6+}	100	Radial	12	5.9-6.7	200	
	C^{4+}	7	Radial	10	2.1-2.9	200	
PRISM	μ	20	Radial	10	6.5	100-1,000	Phase-space rotator
Mu Cooling Ring	μ	160	Radial	12	0.95±0.08		Gas-filled
Neutrino Factory-Japan	μ	20,000	Radial	120	200		Δr=0.5 m ≈ 10 turns, SC magnets, Broadband rf
	μ	10,000	Radial	64	90		
	μ	3,000	Radial	32	30		
	μ	1,000	Radial	16	10		

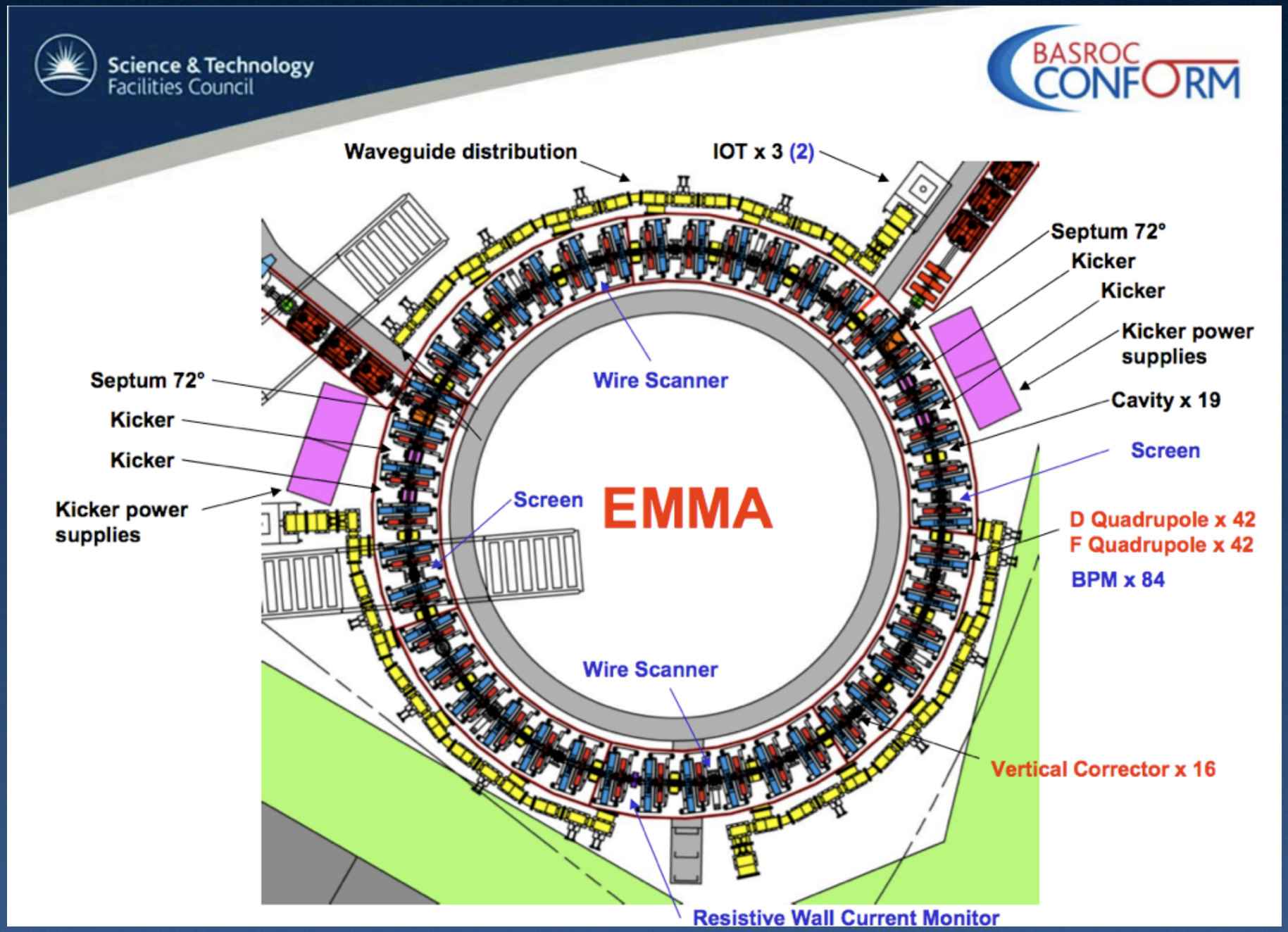
M.K.Craddock, ICFA Beam Dynamics Newsletter No.43, p.22 (2007)

Non-Scaling FFAG

EMMA, Daresbury, UK

- EMMA : Electron Model for Many Applications
- Prove that a NS-FFAG can successfully accelerate particles
  - EMMA is a proof of principle demonstration
- Study linear non-scaling FFAGs under particular circumstances
  - Rapid acceleration
  - Relativistic energies
- Two important characteristics of non-scaling FFAG lattices
  - –Rapid acceleration through many resonances
  - –Unique longitudinal dynamics

EMMA, Daresbury, UK



- under construction, and to be finished in Autumn 2009

High Intensity Beam

FFAG-based high-power proton and ion driver

- Since accelerations of protons were successfully demonstrated at KEK and KURRI up to 150-MeV in Japan, FFAG accelerators are very attractive for the acceleration of high-intensity proton and heavy ions beams.
- The most important feature of the FFAG accelerator is that the magnetic field is kept constant in time, and dose not need to be ramped during the acceleration cycle as in the RCS. Thus the acceleration rate is not limited by the magnetic field but by the accelerating system it self such as rf.
- In the case of acceleration in the low-energy range of heavy particle like protons and heavy ions, the beam velocity varies considerably during acceleration cycle. Freq.-modulated rf cavity system, like using ferrite, will not work for a fast acceleration system with high rep. rate.
- A high rep. rate is desirable to boost the beam power, to avoid problem with space charge and resonance crossing, and also to ease the performance requirements of the ion source and multi-turn injection.
- Selection on acceleration method is important for FFAGs.

Possible Acceleration Methods

- Vary the rf freq. as beam accelerate
  - rf freq. modulation ferrite cores : ~ a few MHz/ms
  - broad-band cavities with MA (Finemet) cores
- Harmonic Number Jump (HNJ)
  - pulse mode
  - CW mode
- Magnetic Induction
  - used only in very low-energy machines
- Gutter Acceleration
  - EMMA for muon acceleration
- Constant rf freq. with Isochronous FFAG

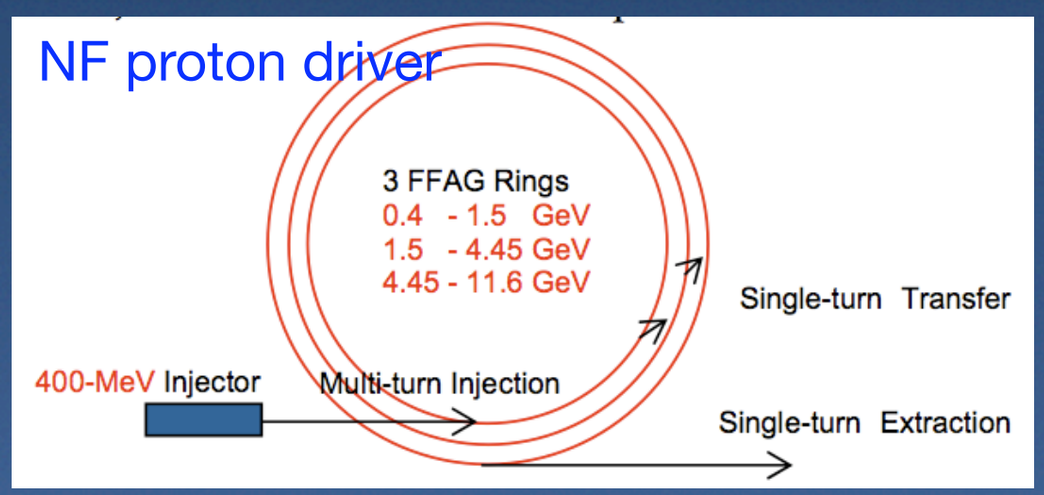
Harmonic Number Jump acceleration

- Difference of revolution period between n-th and (n-1)-th turn equals m(integer) times rf period.
- $T_n - T_{n-1} = T_{rf} \times m$
  - Tn : revolution period for n-turn
  - Trf : rf period
  - m : integer (<0: before, >0: after transition)
- The cavities have constant frequency in the hundreds of MHz range, and possibly in the GHz range. Thus SC cavities with a high gradient is possible to use. But this method requires a programmed energy gain per cavity crossing that can be obtained with an almost linear profile across the radial width of the cavity.
- HNJ was studied for
  - proton and ion acceleration with non-scaling FFAG by A.Ruggiero
  - muon acceleration with scaling-FFAG by Y.Mori

High-energy proton and heavy-ion drivers

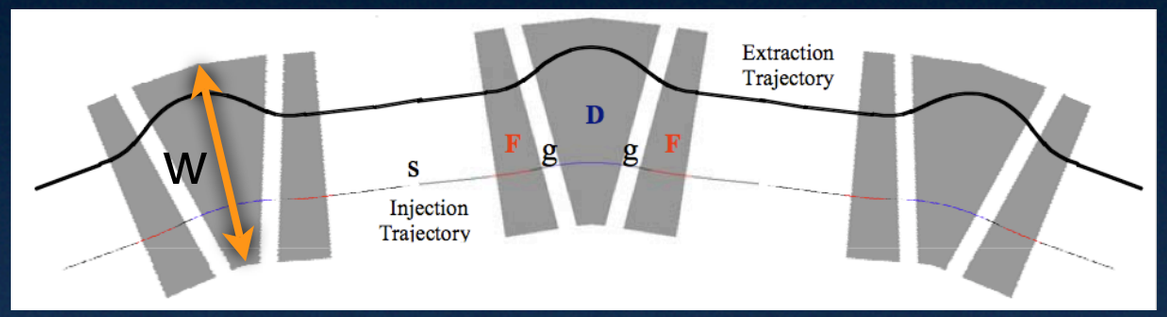
- Using LNS-FFAGs

	Ion	E_{fin} (GeV/u)	E_{inj} (GeV/u)	Rep. Rate (Hz)	Ave. Power (MW)	Ave. Current (mA[-ion])	No. of Rings	C (m)	Ring Structure	Acc, Scheme	Reference
Injector to BNL AGS	p	1.5	0.4	2.5-5.0	0.050	0.033	1	907	A	ferrite cavity	A.G. Ruggiero et al, EPAC04 WEODCH01
NF proton driver (pulse)	p	12	0.4	50	4	0.33	3	907	A	ferrite cavity	A.G. Ruggiero, Nucl.Phys.B (proc. Suppl.) 155 (2006) 315-317
NF proton driver (CW)	p	12	0.4	CW	100	8.5	3	907	A	HNJ	A.G. Ruggiero, BNL report C-A/AP/66
Low energy acc. with high rep rate	p	1	0.050	1k-CW	100	10	2	204	B	MA cavity / HNJ	A.G. Ruggiero, ICFA-HB2004
Rare-isotope production	^{238}U	0.40	0.015	1k-CW	0.40	0.0042	2	204	B	MA cavity / HNJ	A.G. Ruggiero et al, PAC07 TUPAS104



FFAGs

ex. Low-energy proton acc. with high rep. rate



The FDF-Triplet Period of a NS-FFAG Ring

Two main parameters s and w. optimized to ensure beam stability over required mom. range and reasonable magnet size and drift length.

Curcumference, m	204
Number of Periods	80
Period Length, m	2.55
Long Drift *s*, m	1.089
Short Drift *g*, m	0.129
F-Sector Arc Length, m	0.301
D-Sector Arc Length, m	0.602
Radial Width *w*, cm	11.2

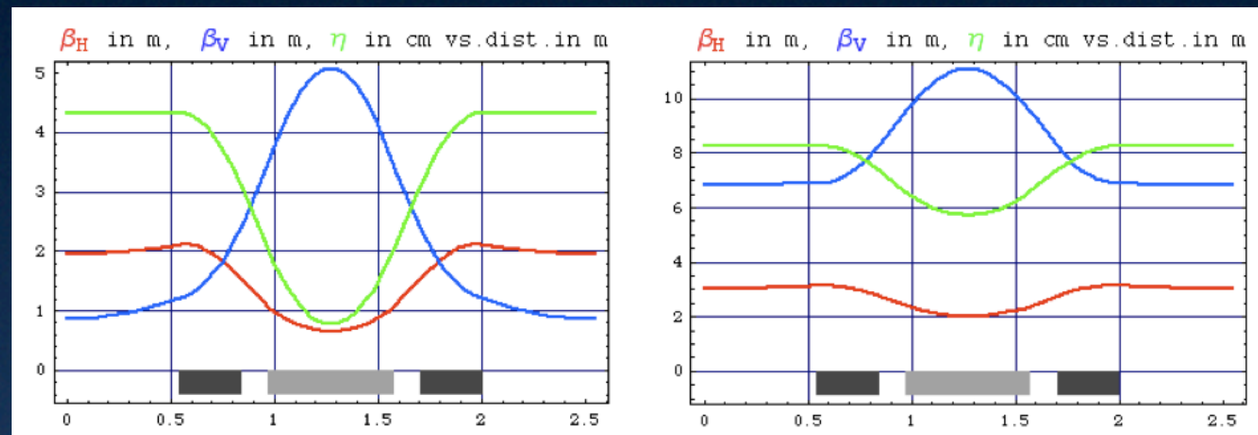


Figure 4: Lattice Functions along the length of a period (Project D).

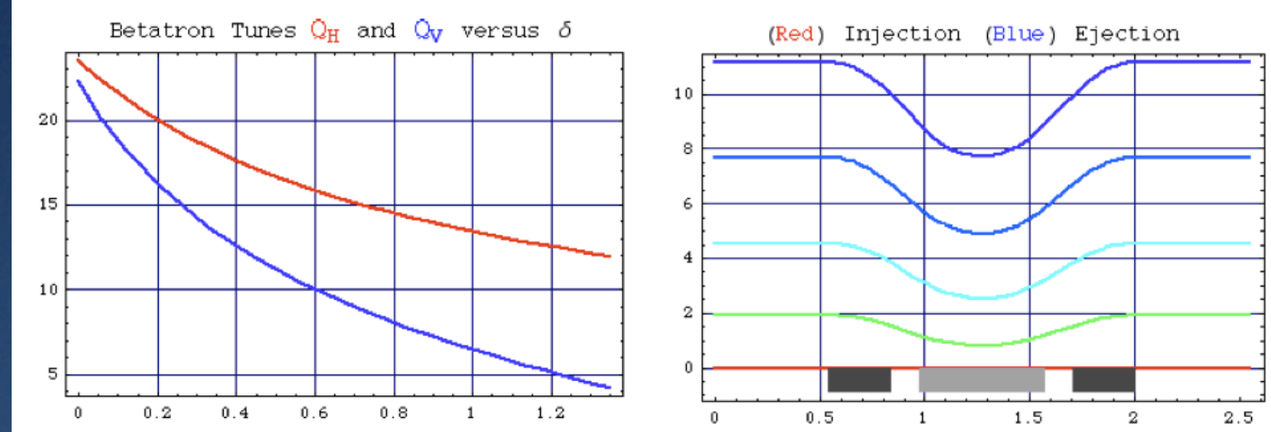


Figure 5: Betatron Tunes and Closed Orbits during the Acceleration Cycle (Project D).

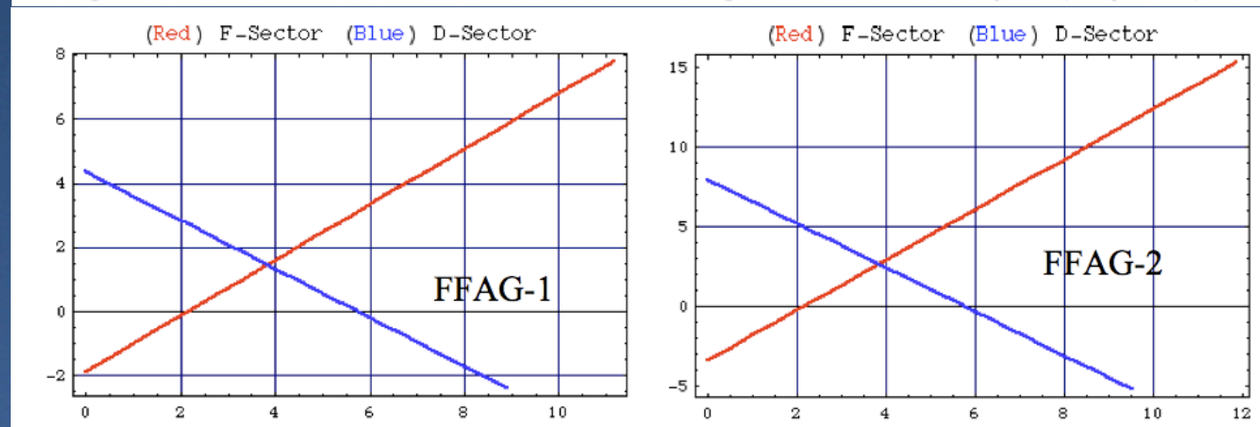


Figure 6: Field Profiles (kG) in the two FFAG Rings vs. Radial location x (cm) (Project D).

ex. Low-energy proton acc. with high rep. rate (cont.)

Table 1: RF Parameters for Acceleration with HNJ in two FFAG Proton Drivers.

	FFAG-1	***FFAG-2***
Cavity Groups	4	2
Cavities per Group	8	16
RF Frequency, MHz	804.9	804.4
h, total	(436 – 223) x 4	(446 – 313) x 2
β_0	0.40	0.80
Cavity Gap g, cm	7.45	14.9
RF Phase	30°	60°
RF Voltage / Cavity, MVolt	6	25
Acceleration Period, μs	87.1	62.7
No. of Revolutions	53 + 1/4	66 + 1/2

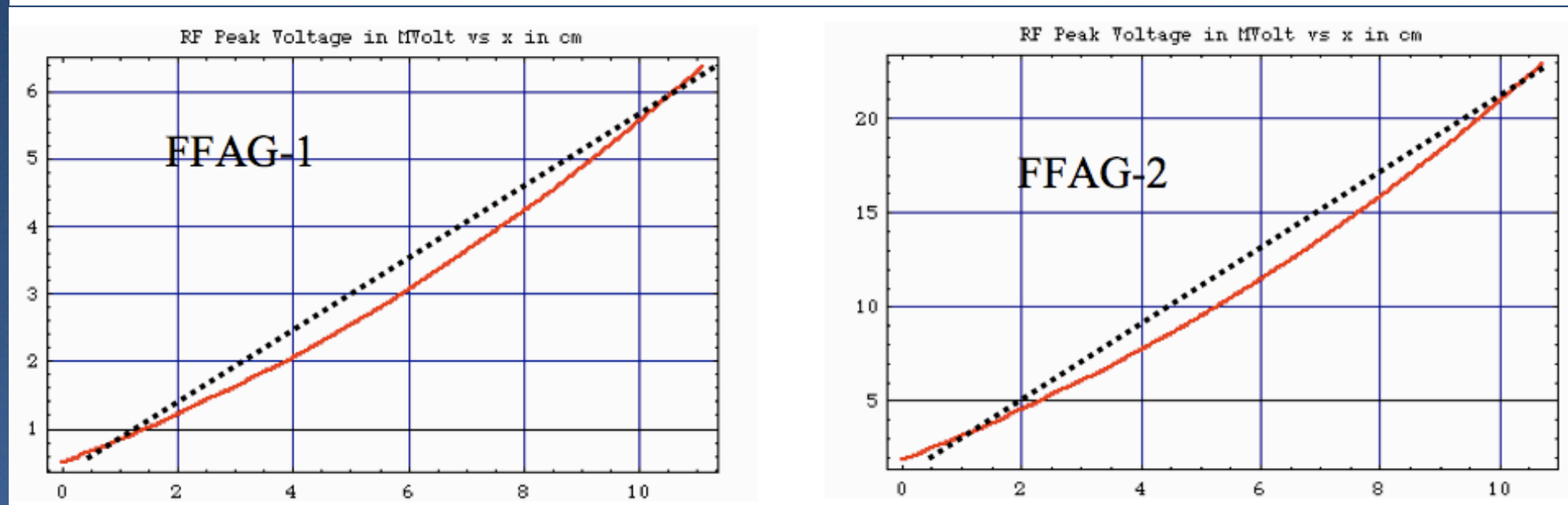
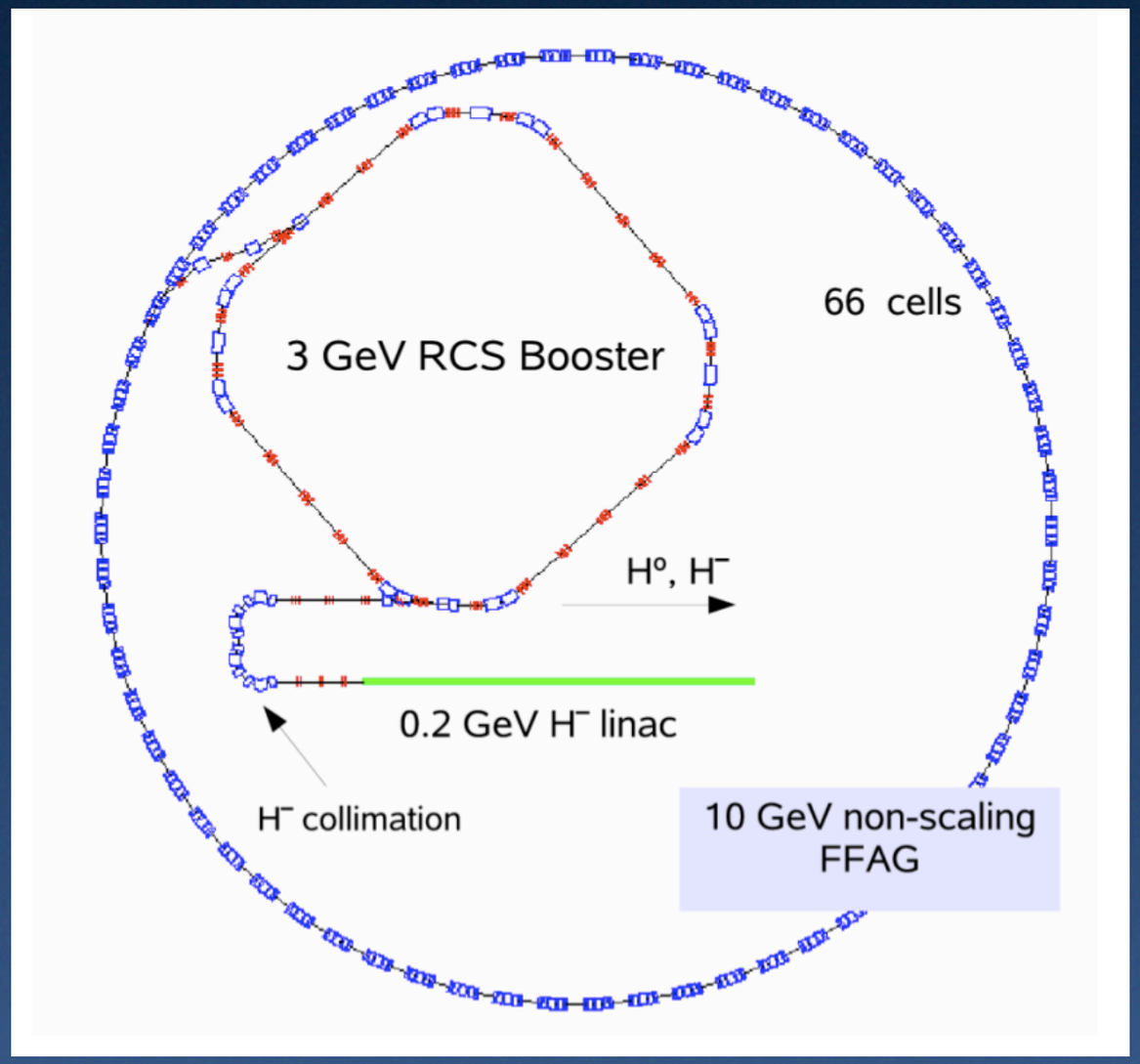


Figure 4: RF Voltage Profile in MVolt vs. Radial Displacement x in cm

An FFAG proton driver for a Neutrino factory

G.H. Rees, Neutrino Factory, International Scoping Study (ISS) Report

- Proton driver for a Neutrino factory
  - 50 Hz, 4 MW, 10 GeV
  - 200 MeV H^- linac
  - 3 GeV booster synchrotron
  - 10 GeV NFFAG driver
- Advantages of NFFAG
  - a high duty cycle, lower rf field
  - metallic vacuum chamber
  - easy adiabatic compression



- NFFAG (non-isochronous, non-linear and non-scaling) should be tested by a low-energy electron model of an NFFAG ring.

Summary

- The history and status of FFAG accelerators were reviewed (very quickly) with their achievements and schedule.
- For scaling FFAG, 8 FFAGs in Japan and 1 FFAG in US were build and operated successfully, aiming the prototype or demonstrator for medical, industrial, and HEP applications. And also many design studies.
- There are also many studies on non-scaling FFAGs for various application: medical, NF and MC etc. Construction of the 1st non-scaling FFAG named EMMA will be completed in Autumn 2009, to prove that a NS-FFAG can successfully accelerate particles.
- Fixed field of FFAG enable to get higher rep. rate, thus FFAGs have a potential for a high power proton or ion driver. Various FFAG accelerators have been proposed based on not only non-scaling FFAGs but also scaling FFAGs with many unique acceleration schemes. But new ideas such as non-scaling FFAG lattice and HNJ should be tested using prototype models.
- We need more detailed study and prototyping for FFAG-based high power hadron beam accelerator.

FFAG'08

1st - 5th September 2008 :: University of Manchester Physics Department, Oxford Road, Manchester

Topics Covered

- EMMA, PAMELA, PRISM, RACCAM
- FFAGs for cancer therapy
- FFAGs for muon acceleration
- FFAGs for proton acceleration
- Scaling v. non-scaling FFAGs
- FFAGs for ADS and neutron production

Talks

Please submit the title of your talk via this email link.

http://www.cockcroft.ac.uk/events/FFAG08/index.htm