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Fixed Field Alternating Gradient Rings - overview

Contents

1 A summary of the situation 2

Machines in operation, modelling *4*

2 ADS/Reactor prototyping, KURR-Institute 4

3 ERIT - Energy Recovery Internal Target, KURR-Inst., Kyoto University (2005-2007) 5

4 EMMA - Electron Model of a Muon Accelerator 6

5 PRISM - Phase Rotated Intense Slow Muon source 8

6 RACCAM - R&D Accélérateurs et Applications Médicales 9

Design studies *12*

7 The Neutrino Factory 12

8 Proton machines methods, applications 13

1 A summary of the situation

- Up to now 9 FFAG machines have been constructed and operated :

  - 3 electron models by MURA Lab., 100keVs and MeVs range, 1950's

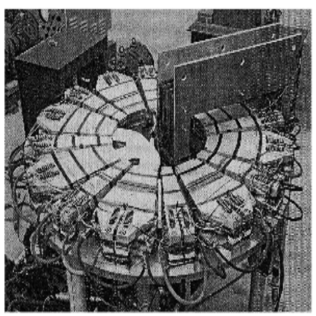
CARE-HHH, C

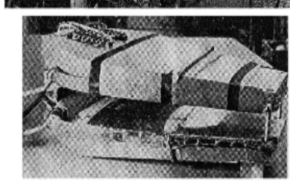
The first model, radial sector FFAG, Mark II

Main optical feature : fixed field $B = B_0(r/r_0)^K F(\theta)$, hence zero chromaticity, "scaling".

Objectives : confirm theoretical predictions ; study FFAG properties : optics, injection, test RF progra of misalignments ; effects of resonances.

First operation March 1956, U of Michigan.





F magnet, positive field, radially focusing.

Machine parameters			criteri
$E_{inj} - E_{max}$	keV	25 - 400	$\{$small size, field not to
orbit radius ($\mathcal{C}/2\pi$)	m	0.34 - 0.50	SPIRA
Optics			STRONG FOCUSING, SCALIN
lattice		$\frac{D}{2}F\frac{D}{2}$	
number of cells		8	16 magne
field index K		3.36	g/r =Cs
ν_r / ν_z		2.2-3 / 1-3	$\{$varying varies m
γ_t		≈ 2	
Magnet		radial sector	$B = B$
θ_F, θ_D	deg	25.74, 10.44	sec
$r_{F,D}/\rho$		2.85, 2.59	at center
gap	cm	6 - 4	g
Injection		continuous or pulsed	
Acceleration		only betatron, at first...	for
swing	Gauss	40 - 150	
rep. rate	Hz	a few 10's	
		... completed with RF acc., next	s
freq. swing	MHz	10 in [35, 75] MHz	for RF
gap voltage	V	50	

Second model, spiral sector FFAG, Mark V

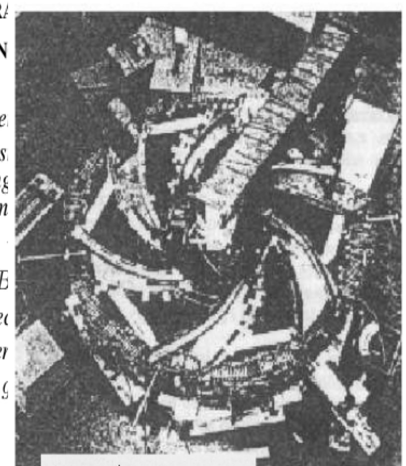
The idea in the spiral FFAG was to superpose a positive field on top of the alternating sign one of the radial sector, so as to always have the right curvature and decrease the circumference factor.

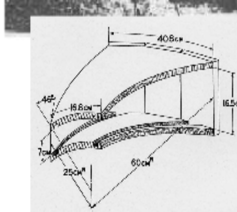
By doing so, vertical focusing is altered, hence additional edge focusing using spiral shape.

Interest of spiral optics : always positive curvature, hence smaller accelerator, compared to radial sector.

Study objectives : confirm theoretical predictions - first extensive use of computers to determine magnetic field and machine parameters ; long-term orbit stability ; RF acceleration methods.

First operation Aug. 1957 at the MURA Lab., Madison.





Logarithmic spiral poles

Machine parameters			criteria / comments
$E_{inj} - E_{max}$	keV	35 - 180	$\{$reasonable size magnets
orbit radius	m	0.34 - 0.52	SPIRALING ORBIT
E_{tr} / r_{tr}	keV / m	155 / 0.49	$\{$RF exprmnts at $\gamma_{tr} = (1+K)^{1/2}$
Optics		STRONG FOCUSING,	SCALING $\rightarrow \xi = 0$
lattice		N spiral sectors	
number of sectors		6	
field index K		0.7	$\{$coil windings, tunable 0.2-1.16
flutter F_{eff}		1.1	tuning coils / 0.57 - 1.6
ν_r / ν_z		1.4 / 1.2	tunable
β_r / β_z	m	0.45-1.3 / 0.6-1.4	min-max
Magnet		spiral sector	B=$B_0(\frac{r}{r_0})^K F(\ln\frac{r}{r_0}/w -$
$1/w$		6.25	$2\pi w r_0 \approx$ ridges radial sepa
$\alpha = Arctg(Nw)$	deg	46	edge to radius angle
$r_{min} - r_{max}$	m	0.25 - 0.61	
gap	cm	16.5 - 7	g/r =Cte
Injection		cont. or pulsed	e-gun + e-inflector
Acceleration		betatron and RF	extensive RF prog. test

1 A summary of the situation

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  - 2 proton rings, at KEK, 500 keV and 150 MeV (now transfered to Kyushu Univ.), beam 2000 & 2003 resp.

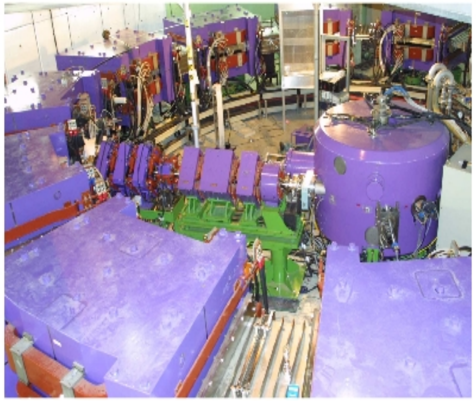
2 KEK proton machines

- **POP - Proof of principle, the first proton**

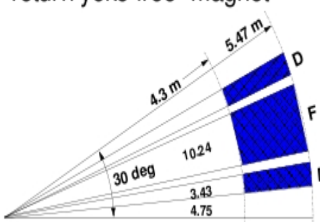
First beam 2000.

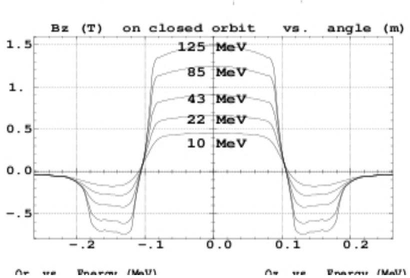
[Typical] data

$E_{inj} - E_{max}$	keV	50 - 500
orbit radius	m	0.8 - 1.14
Optics		
lattice		DFD
number of cells		8
K		2.5
β_r, β_z max.	m	0.7
ν_r / ν_z		2.2 / 1.25
Magnet	high field, non-linear gradient	
θ_D / θ_F, core	deg	2.8 / 14
B_D / B_F	T	0.04-0.13 / 0.14-0.32
gap	cm	30-9
Injection		multi- or single-turn



"return yoke free" magnet





- **The 150 MeV machine**

First operation 2003.

[Typical] data

$E_{inj} - E_{max}$	MeV	12 - 150	
orbit radius	m	4.47 - 5.20	
Optics			
lattice		DFD	9
numb. of cells		12	
K		7.6	$(B =$
β_r / β_z max.	m	2.5 / 4.5	
ν_r / ν_z		3.7 / 1.3	*tunable*
α, γ_{tr}		0.13, 2.95	$1/(1+$
$\mathcal{R}/\rho\vert_{E_{max}}$		5.4	
Magnet	**Return yoke free magnet**		
θ_D / θ_F	deg	3.43 / 10.24	
B_D / B_F	T	0.2-0.78 / 0.5-1.63	r
gap	cm	23.2 - 4.2	*at* r_{inj} - r_m
Injection		multi-turn	{ B-se, +
Extraction		single-turn	**fast kic**
Acceleration	*Amorphous MA,*	**broad band, high gra**	
swing	MHz	1.5 - 4.5	
harmonic		1	

1 A summary of the situation

- Up to now 9 FFAG machines have been constructed and operated :
  - 3 electron models by MURA Lab., 100keVs and MeVs range, 1950's
  - 2 proton rings, at KEK, 500 keV and 150 MeV (now transfered to Kyushu Univ.), beam 2000 & 2003 resp.
  - a 150 MeV triple-ring assembly, part of ADS prototyping, KURR-Institute, started 2006
  - internal target storage ring for neutron production, Kyoto Univ., 2007
- Constructions in progress :
  - EMMA, 10-20 MeV e-model of linear FFAG, Daresbury
  - PRISM, a ring for muon bunch capture and compression, Osaka Univ.
  - spiral lattice design and magnet prototyping, RACCAM ANR project, Grenoble

In addition, design studies

- Muon accelerators in the Neutrino factory, in the frame of IDS-NuFact, EURONu, EUCARD/ANAC
- Proton driver methods, in UK, at BNL
- Several medical projects, e.g. Oxford, FermiLab, Japan, Grenoble

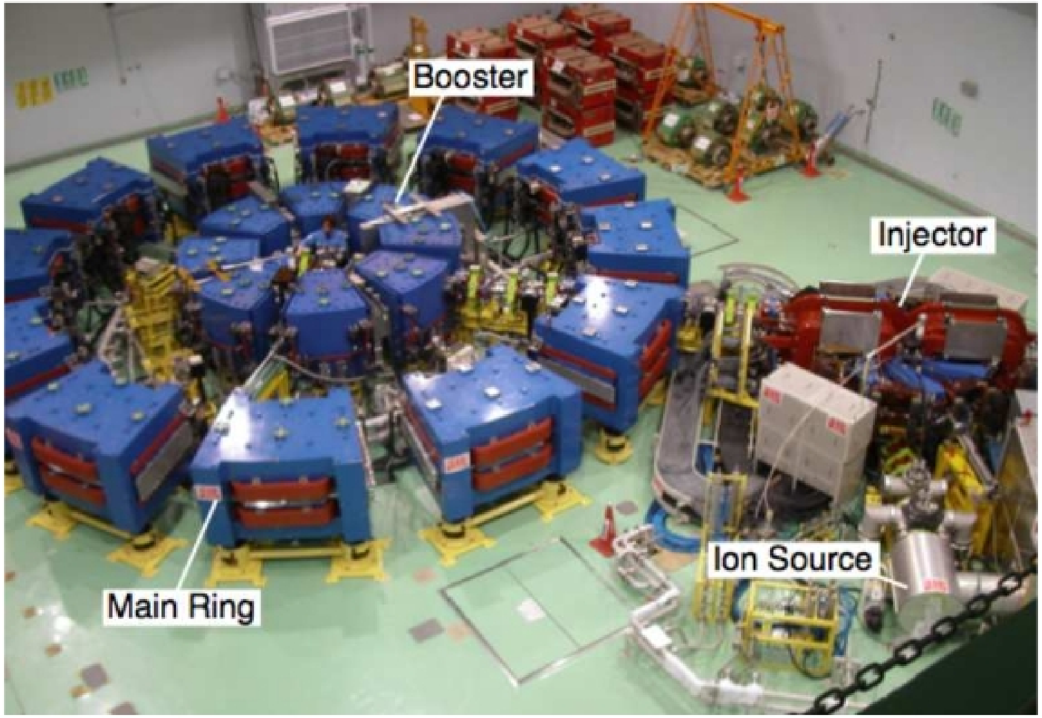
* 17 workshops in 9 years *

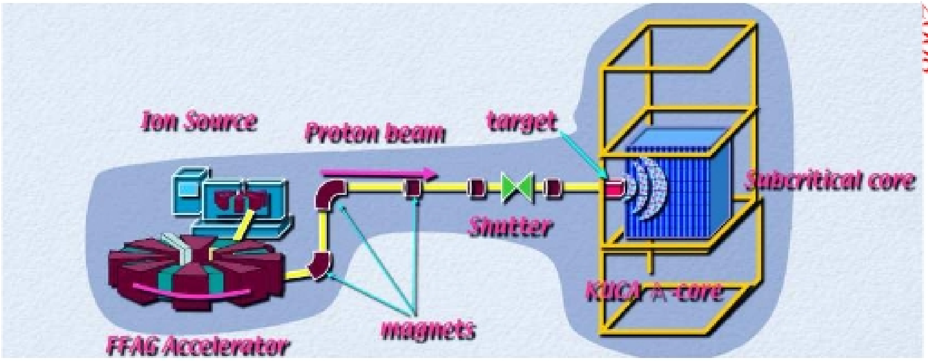
• 1st	Dec. 1999	KEK
• 2nd	July 2000	CERN
• 3rd	Oct. 2000	KEK
• 4th	Feb. 2002	KEK
• 5th	Sept. 2002	LBL
• 6th	July 2003	KEK
• 7th	Sept. 2003	BNL
• 8th	Mar. 2004	TRIUMF
• 9th	Oct. 2004	KEK
• 10th	Apr. 2005	FNAL
• 11th	Dec. 2005	KURR-Institute
• 12th	Apr. 2006	BNL
• 13th	Nov. 2006	KURR-Institute
• 14th	Apr. 2007	IN2P3/LPSC
• 15th	Nov. 2007	KURR-Institute
• 16th	Sept. 2008	Manchester
• 17th	Nov. 2008	KURR-Institute

Machines in operation, modelling

2 ADS/Reactor prototyping, KURR-Institute

ADS/Reactor *and* accelerator prototyping, output power $\sim$10 W
Beam power needed from FFAG < 0.1 W (typically 100 MeV, <1 nA)
Further (longer term) objectives from accelerator installation : 25-150 MeV p beam, up to 1 μA (120 Hz)
Now operated at 100 MeV, 0.1 nA, beam extracted towards 5W reactor core

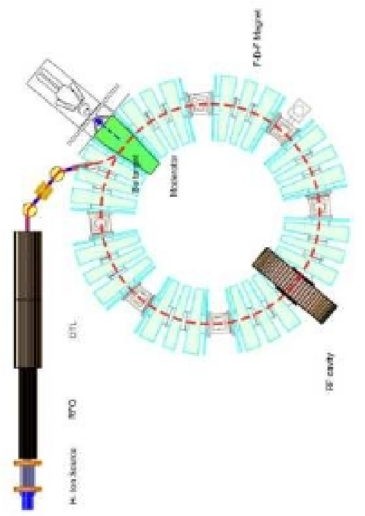




B ~ r^K

3 ERIT - Energy Recovery Internal Target, KURR-Inst., Kyoto University (2005-2007)

Prototype of compact accelerator for BNCT, epithermal n source, E< 15 MeV
High flux needed at patient : 10 cm^2 tumor, $2\,10^{13}$n, 30'.
Today, (5-10 MW) n reactor used, there is need for hospital equipment : ERIT
Internal target causes 6-D emittance growth, requires large acceptance,
in particular large $\Delta p/p \approx 10\%$ hence zero-chromaticity essential.
Storage, $\sim$1000-turn survival, allows low injection current.



Injector(425 MHz RFQ + IH-DTL)

H- kinetic energy 11 MeV
Peak/average beam current 5 mA / $>$100 μA
Repetition rate 200 Hz, D.C. 2%

FFAG ring

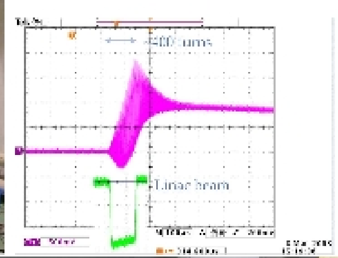
FDF lattice, 8 cells
H- injection on Be target
proton kinetic energy 11 MeV
Circulating beam current 70 mA

ERIT system

Beam survival 500-1000 turns
Internal target Be 5-10 μm, lifetime $>$1 month
ΔE/turn 70 keV

RF cavity

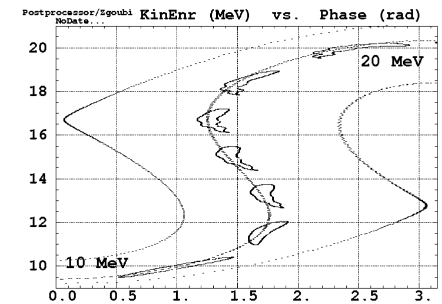
Operated CW, 100 kW input power
RF voltage / frequency 250 kV / 18.1 MHz
Harmonic number 5



Future :

- Machine studies
- Longitudinal cooling with wedge target
- Target life-time
- Biological R&D

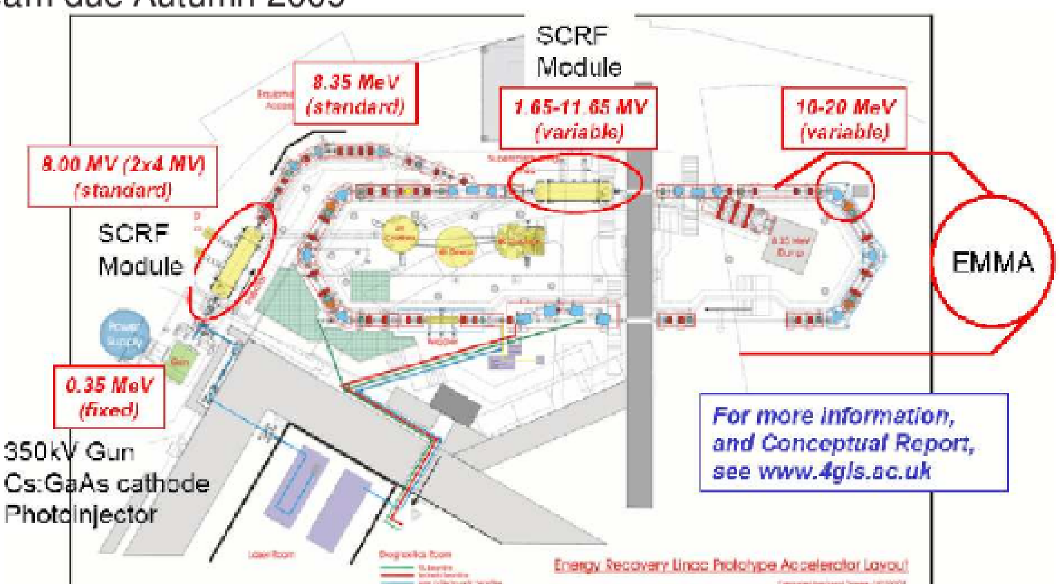
4 EMMA - Electron Model of a Muon Accelerator

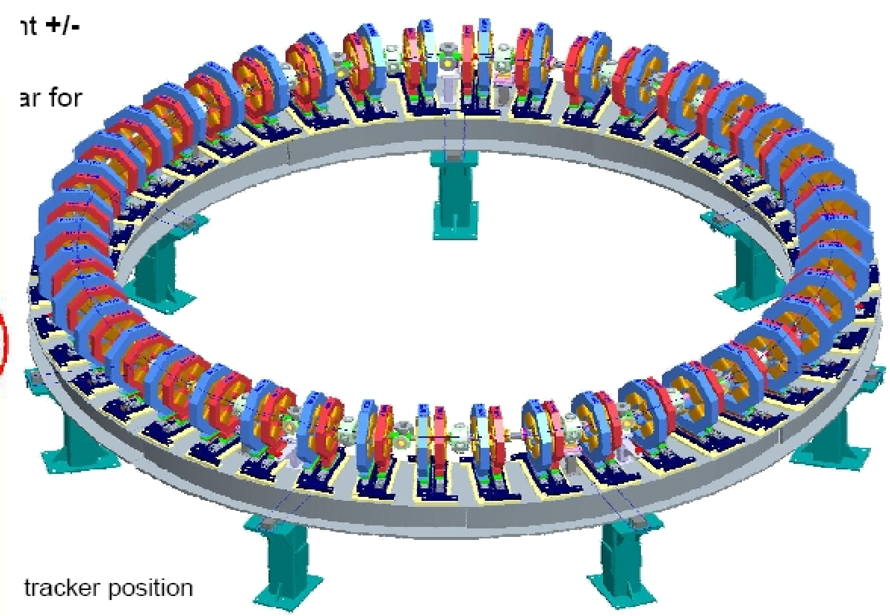


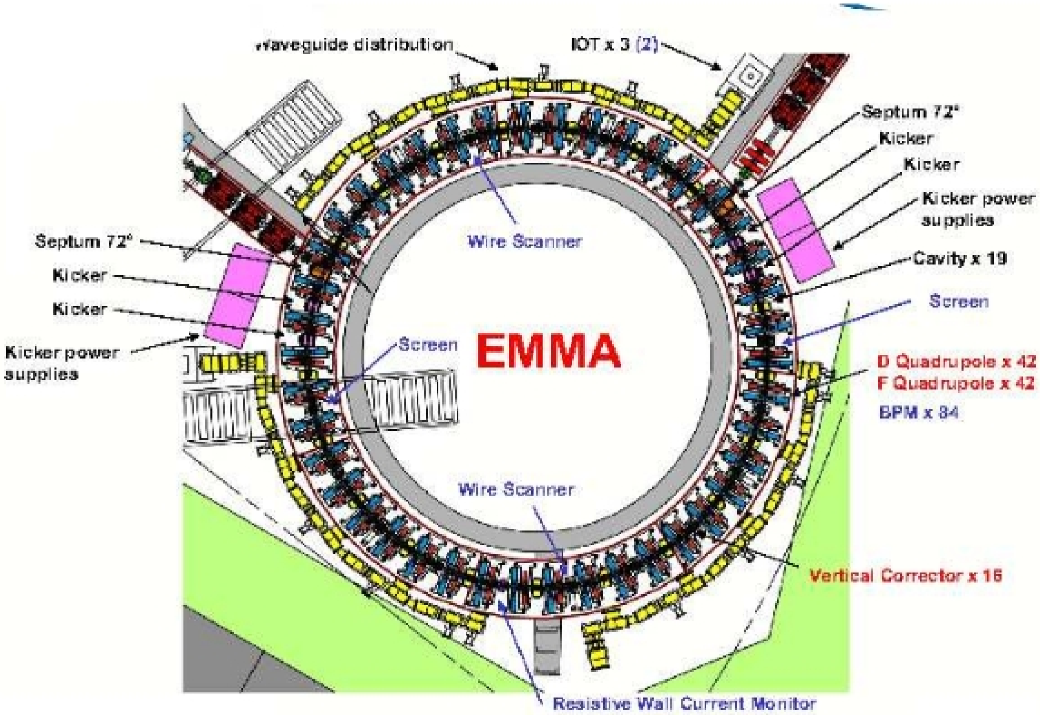
- **Launched in the frame of Neutrino Factory R&D**
- **An experimental model of muon accelerators**
- **International collaboration :**
BNL, CERN, FNAL, LPSC, STFC, J.Adams Inst., Cockcroft Inst., TRIUMF
- **Recollection :**
1999 : principle of linear FFAG optics, FNAL
2001 : first e-model meeting, BNL
2006 : project funded by "British Accelerator Science and Radiation Oncology Consortium", 3.5 years : 04-2007 / 09-2010, £5.6M budget
- **Construction started at Daresbury, 04/2007, first beam planned summer 2009**

- **Goals of EMMA experiment:**
- prove rapid, "gutter acceleration"
- investigate resonance crossing
- assess phase space, dynamic aperture
- investigate sensitivity to defects
- assess stability, operating conditions

Beam due Autumn 2009



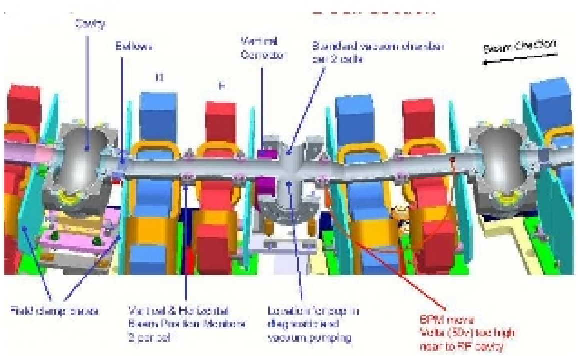




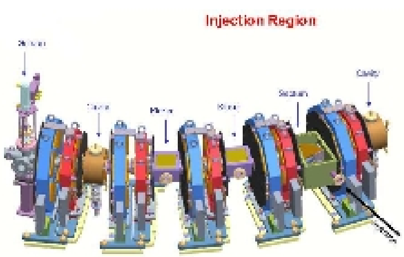
EMMA parameters

Energy range	*MeV*	10 - 20
number of turns		$<$16
circumference	*m*	16.568
Lattice		F/D doublet
No of cells		42
RF frequency / range	*GHz / MHz*	1.3 / 5.6
No of cavities		19
RF voltage	*kV/cav.*	20 - 120
RF power	*kW/cav.*	$<$2
Bunch emittance	πmm	3
Bunch charge	$pC/\mu A$	$<$32
Rep. rate	*Hz*	1-20

CARE-HHH, CERN, November 2008



- cell length	*cm*	39.448
- length F/D	*cm*	5.878 / 7.570
- drifts	*cm*	5 / 21
- gradient at F/D	*T/m*	$\approx$2
- apertures QF/QD/Cav.	*cm*	7.4 / 10.6 / 4
- alignement	μm	0.25 (1σ)



Status :

- Design of the layout of the installation now esssentially complete
- Quads : production complete Autumn 2008.
- RF cavities : delivery Autumn 2008
- Injection/extraction septum magnets, kickers : tenders summer 2008
- Diagnostics : button PU, resistive wall monitor, screen, spectro, F-cup, wire scanner, work in progress

5 PRISM - Phase Rotated Intense Slow Muon source

Goals of PRISM :

• Construct a full size 10-cell FFAG ring for muon experiments

Up to $10^{12}\mu^{\pm}$/s (NuFact range), rep. rate 100Hz

• Develop a high gradient RF system

• Demonstrate phase rotation :

from 68MeV/c +/-20% down to +/-2% in 6 turns

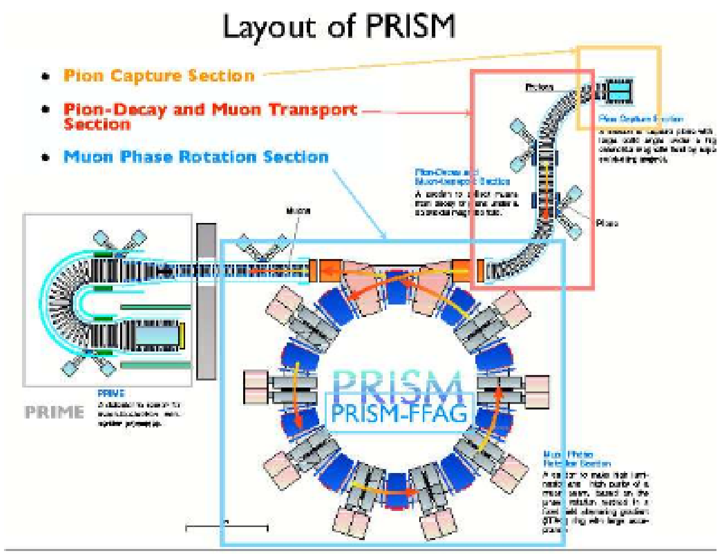
- DFD lattice 14t triplet yoke, 120 kW/triplet
- K, B_F/B_D variable → quasi-decoupled ν_x, ν_z adjustments
- H / V apertures : 1 / 0.3 m
- acceptance : 3.8 π cm × 0.57 π cm
- RF : ≈ 200 kV/m, 2 MV/turn

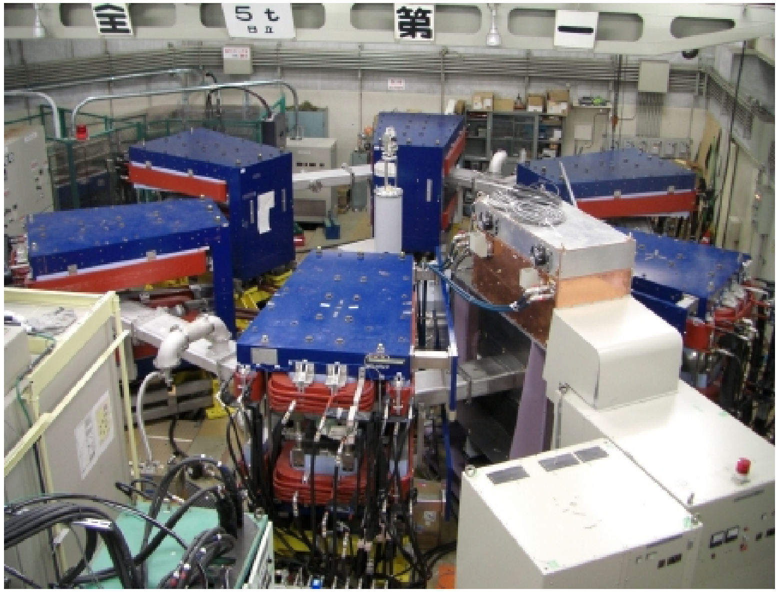
• Status :

- A DFD triplet has been commisionned using α from Am_{241}
- A 6-cell ring has been built at Osaka University
- 2.1 MHz RF system has been developped, 33 kV in gap
- The 6-cell ring is being qualified using alpha beam and internal Am_{241} source : closed orbits, phase advance, benchmarking of simulations, commissioning methods

• Future :

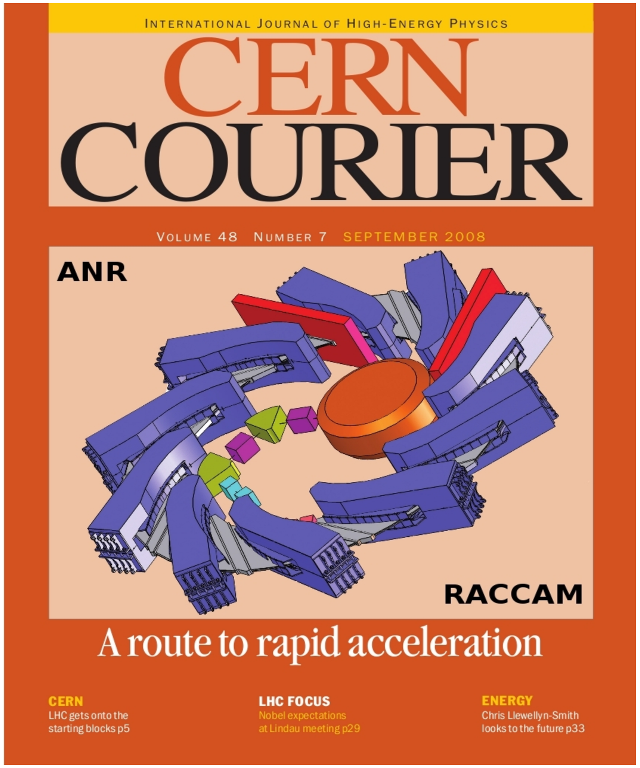
- generation of saw-tooth RF wave for phase rotation
- developement of injection kicker and external injection
- phase rotation

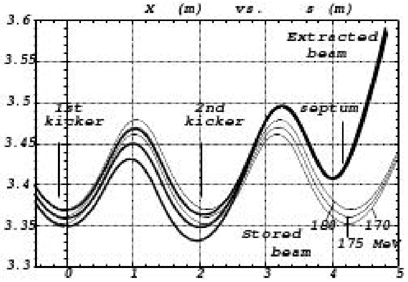


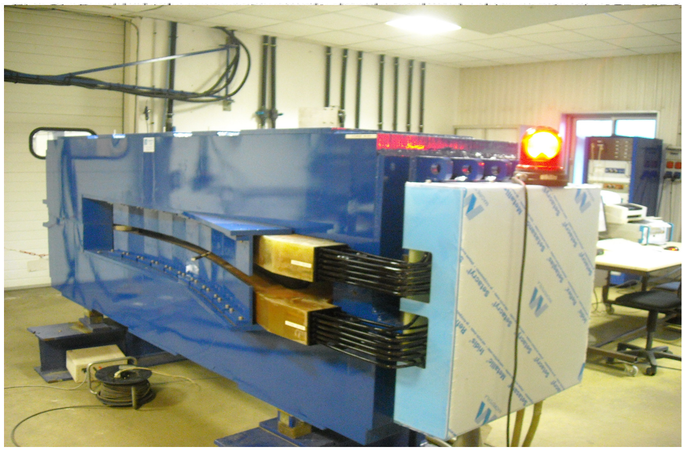


6 RACCAM – 1/ FFAG R&D, NuFact sector
2/ Application to protontherapy

Extracion energy, variable	70 – 180 MeV
Injection energy	5.5 – 17 MeV
Nomentum ratio	3.62
Number of cells	10
Packing factor	0.34
Field index, k	5
Spiral angle	53.7 deg.
Qh / Qv	2.76 / 1.55~1.60
Radius, extraction/injection/dR	3.46 m / 2.78 m / 0.67 m
Drift length, extraction/injection orbit	1.42 m / 1.15 m
Frev, 15->180 MeV	3.03 -> 7.54 MHz
Frev, 5.5->70 MeV	1.86 -> 5.07 MHz







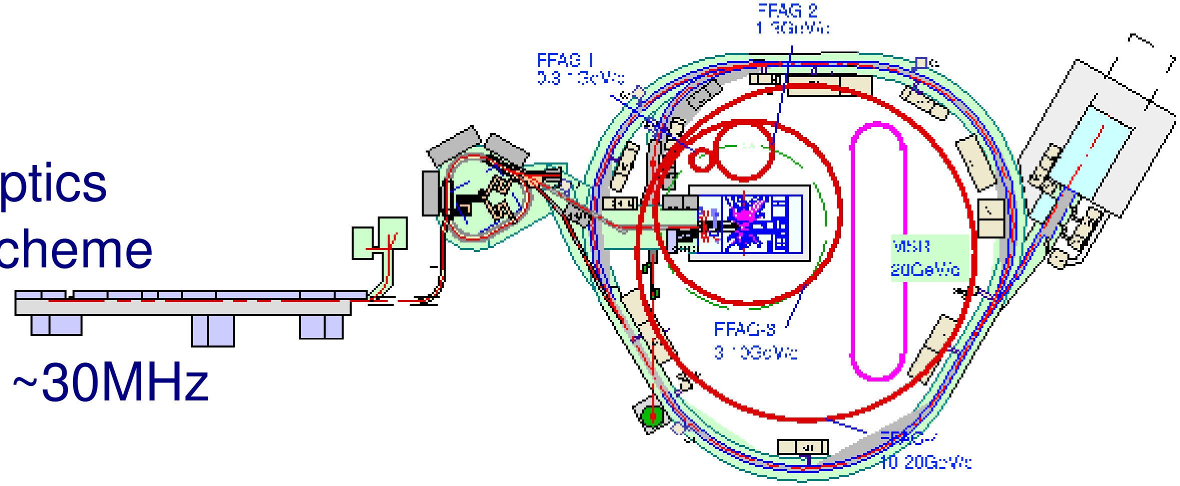
Future :
- RACCAM ends next February
- All objectives completed
- New application for funds fromNational Research Agency, last week

Design studies

7 The neutrino factory : still a huge amount of design studies to do, still a lot to learn

- "Scaling" (tune-invariant) optics
  The japan NuFact scheme

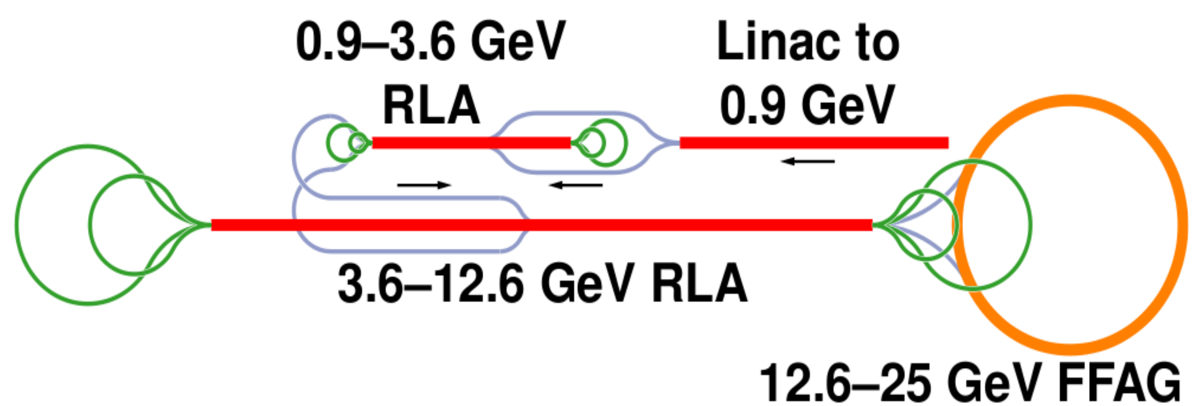
Based on low-frequency RF ~30MHz
Large 6D acceptance



- "Non-scaling" (non tune-invariant) optics
  The IDS-NuFact scheme

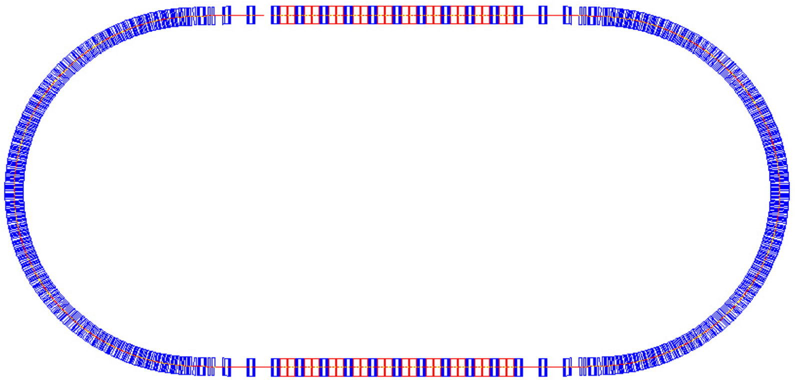
Based on 200 MHz RF, ~1500MV
30 mm transverse acceptance
Circumference ~450m
Quads r / field ~ 10-20cm / 4-8T

IDS Acceleration Scenario



Lots of ideas in the air…
RLA arcs

Multipass Linac - racetrack FFAG

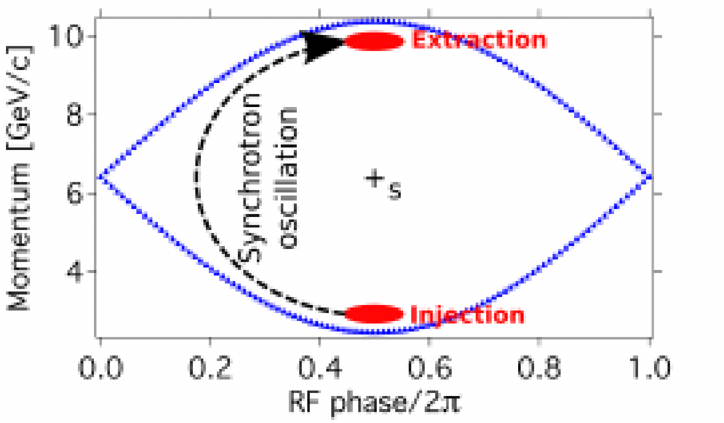


- **Problems:**
  - **Matching of the circular non-scaling FFAG to the straight linac.**
  - **Time of flight adjustments for each pass.**
- **Goals:**
  - **Try to make four or five times in muon energy by either a race track or dog-bone acceleration with *a single arc* (2.5-10 GeV or 10-40 GeV).**
  - **Match the betatron and dispersion functions from the arc to the linac.**
  - **Design a chicane to adjust the time of flight for different energy passes.**

Lots of ideas in the air...
Fast acceleration in scaling FFAG

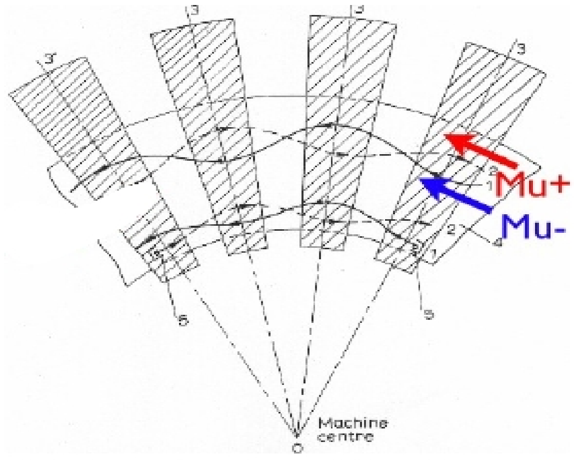
Variable frequency RF is not a good candidate...
Still learning a lot from scaling FFAGs...

Stationary bucket acceleration
$f_{RF} < 100$ Hz
small phase slip, convenient



Harmonic number jump, $T_n - T_{n-1} = p / f_{RF}$
$f_{RF > 100\ Hz}$

compatiblity with two-beam ring ?



8 Other linear lattice design studies

Several Labs contribute in EU (mostly UK), US (Fermilab, BNL) :

linear lattices for ADS application, PAMELA (medical, p/C) ...,

large momentum-bite tune-invariant lattice,

fast acceleration methods

etc.

Thank you for your attention