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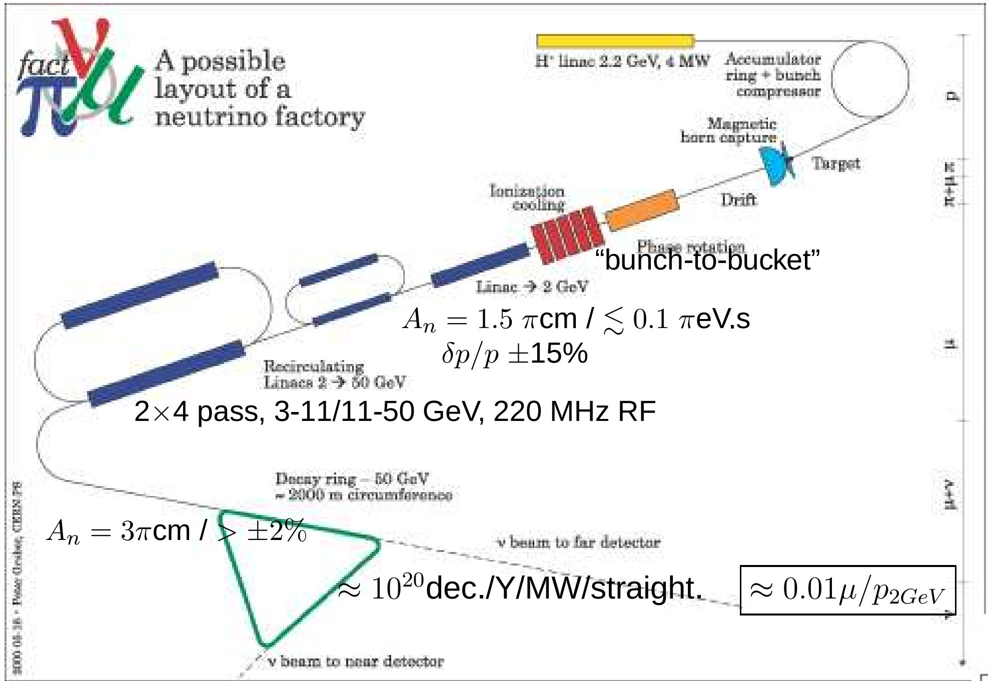
Muon acceleration, FFAG studies. Present status

Contents

1 Pre-FFAG era : RLA based designs

Principle : high freq./high gradient RF $\rightarrow$ fast acceleration (+ large phys. aperture) $\rightarrow$ high μ transmission

- **Europe NuFact** [rep. March 2003]



Amongst conclusions to these design studies :

. difficult projects, yet no fundamental obstacle

. plans for extensive R&D, prototyping, tests

. very high cost

$->$ US SII report, introduction to Chapt.6 (Acceleration) :

"FFAG rings could be also considered"

- **US Study I** [1999-200, rep. April 2000]
16 GeV, 1 MW p-driver
capture/ϕ-rotation/bunching/cooling/pre-accel
2 RLA's : 3 $\rightarrow$ 8 $\rightarrow$ 50 GeV,
a "low" $2\ 10^{19}$ decays/Y/MW/straight
- **US Study II** [rep. 2002], a follow-on
based on 1MW upgraded AGS + Hg jet target
Single RLA, 200 MHz SCRF,
improved $1.2\ 10^{20}$ decays/Y/MW/straight

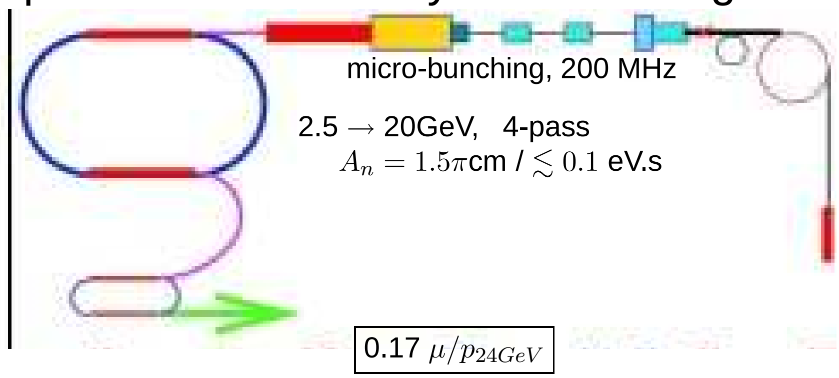


Table A.1: Construction Cost Rollup per Components for Study-II Neutrino Factory. All costs are in FY01 dollars.

System	Magnets ($M)	RF power ($M)	RF cav. ($M)	Vac. ($M)	PS ($M)	Diagn. ($M)	Cryo ($M)	Util. ($M)	Conv. Facil. ($M)	Sum ($M)
Proton Driver	5.5	7.0	66.1	9.8	26.6	2.2	28.5		21.9	167.6
Target Systems	30.3			0.8	3.5	8.0	18.8		30.2	91.6
Decay Channel	3.1			0.2	0.1	1.0	0.2			4.6
Induction Linacs	35.0		90.3	4.4	163.3	3.0	3.6		19.5	319.1
Bunching	48.8	6.5	3.2	2.7	2.1	5.0	0.3			68.6
Cooling Channel	127.6	105.6	17.7	4.3	4.8	28.0	9.5		19.5	317.0
Pre-accel. linac	46.3	68.4	44.1	7.5	3.0	6.0	13.6			188.9
RLA	129.0	89.2	63.4	16.4	5.6	4.0	28.9		19.0	355.5
Storage Ring	38.5			4.8	2.2	20.0	4.8		28.1	107.4
Site Utilities								126.9		126.9
Totals	464.1	276.7	284.8	50.9	211.2	86.2	108.2	126.9	138.2	1,747.2

- **Study IIa** , larger A_n, FFAG $\rightarrow$ less cooling ?

2 Japan NuFact. Scaling FFAG R&D

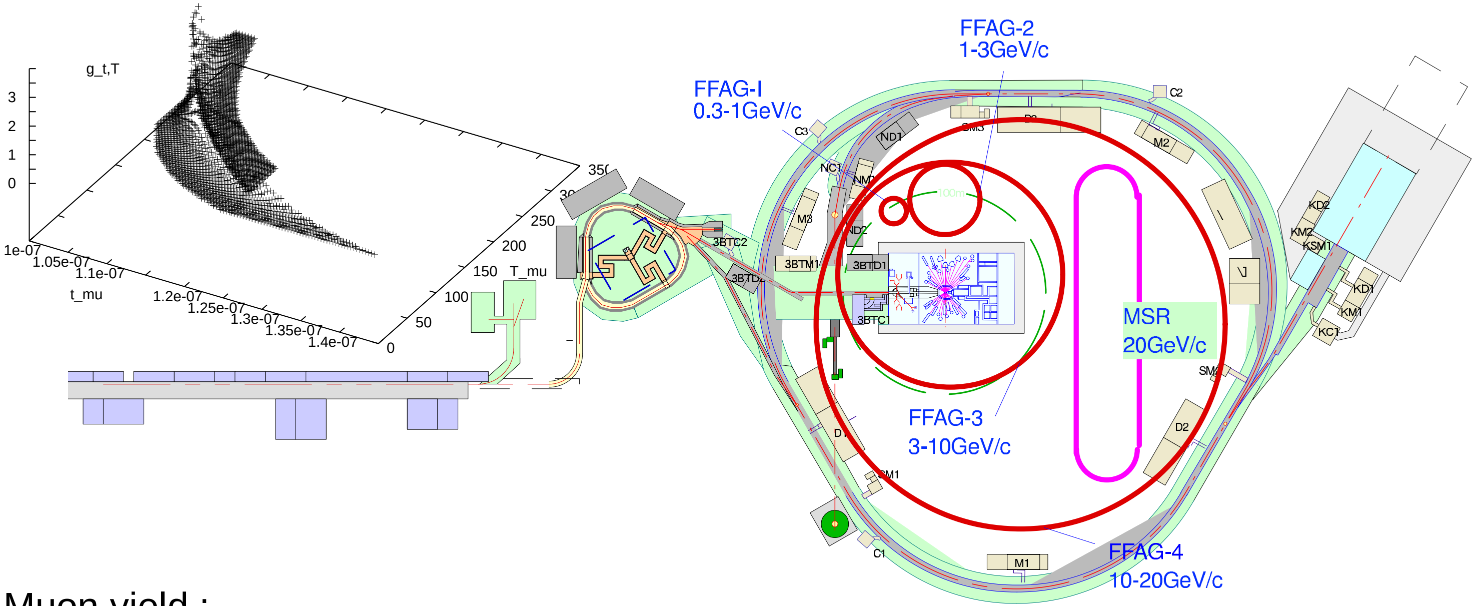
- p-Driver : JPARC installation, 50-GeV, $3.3\,10^{14}$ ppp, 8 b/p, 0.3 Hz rep. rate / 0.75 MW (first beam 2006)

- Four muon FFAG's : 0.2-1 GeV, 1-3, 3-10 (SC), 10-20 (SC), [reasonable E span / magnet ΔR]
- using high gradient (in 10 MV/m range) / low frequency RF (5-25 MHz) [fast acceleration / large ϵ_l]

Interest of the FFAG method :

- compact (R≈200 m), technology simpler (potentially cheaper), can be built earlier (less R&D)
- cooling : longitudinal can be avoided : low freq. RF → large longitudinal acceptance (expected ± 50% at injection)
- potential for transverse cooling in 1st ring

20ns/300±50% MeV bunch captured, $\approx 1.5\ \pi$eV.s

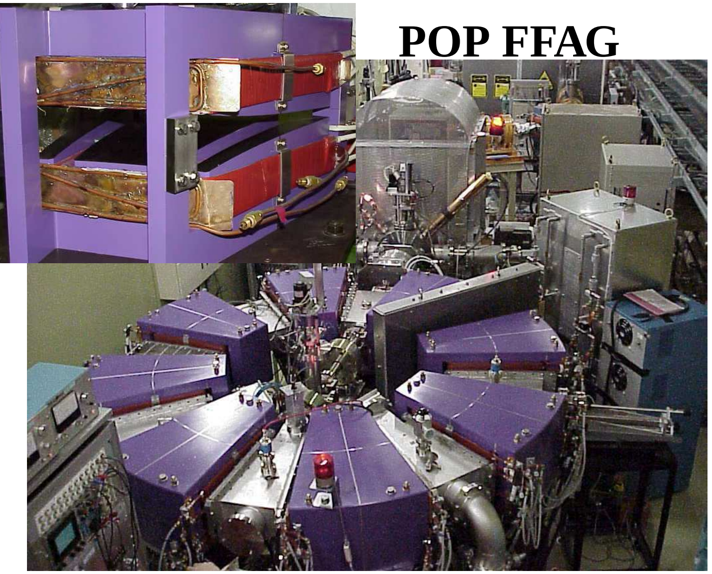


Muon yield :

- Acceleration rate ≈ 1 MV/m on average (cf RLA, 5 MV/m range), hence large acceleration distance, transmission about 50% (cf. 75% of US Study II RLA scheme)
- yet acceptance is large transversally, about $3\ \pi$cm norm. ; longitudinal in range 1.5 π eV.s.
- it results **[muon yield close to 0.3 /p$_{50GeV}$]**, $\xrightarrow{\times 10^{21} p/Y\ /3}$ $> 2\,10^{20}$ dec./Y/MW/straight

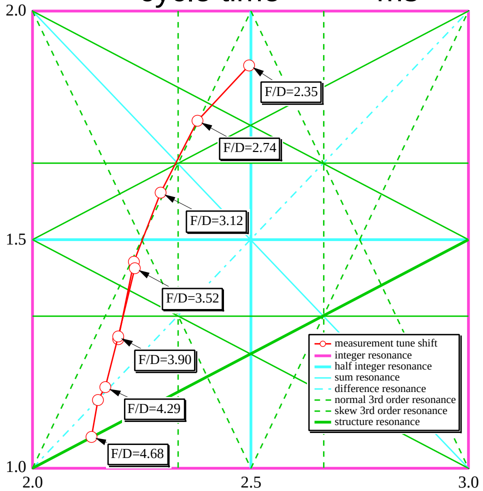
Extensive R&D programs : BD, NC/SC magnets, high gradient RF, rapid cycling, extraction ...

POP FFAG



First accelerated beam 1999

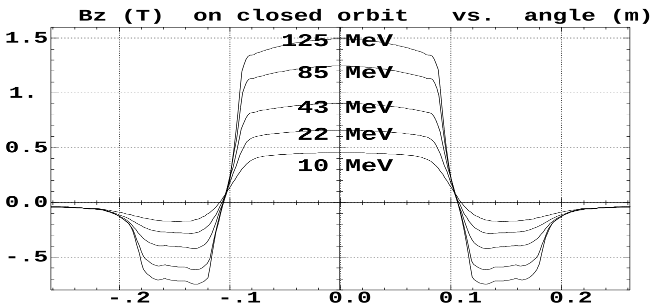
$E_{inj} - E_{max}$	keV	50 - 500
orbit radius	m	0.8 - 1.14
lattice / K		DFD $\times$ 8 / 2.5
$\beta_r,\ \beta_z$ max.	m	0.7
$\nu_r\ /\ \nu_z$		2.2 / 1.25
RF swing	MHz	0.6 - 1.4
voltage p-to-p	kV	1.3 - 3
cycle time	ms	1



150 MeV FFAG

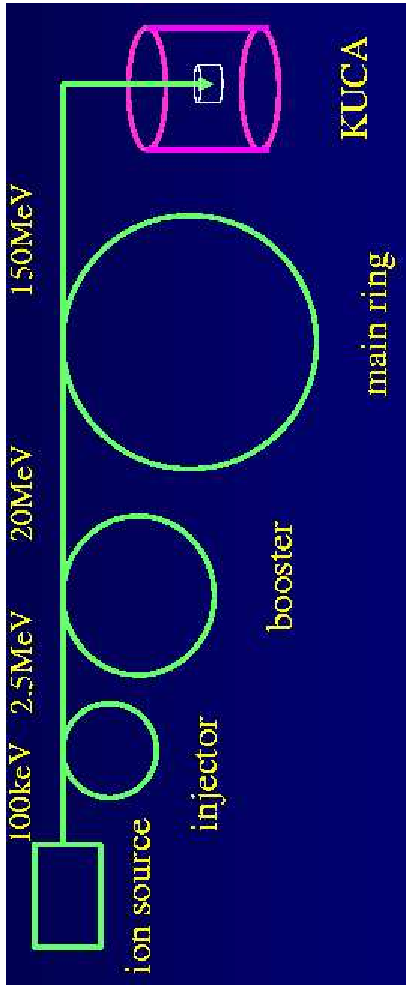
First beam 2003. Reached 100 MeV full ΔR

$E_{inj} - E_{max}$	MeV	12 - 150
orbit radius	m	4.47 - 5.20
lattice / K		DFD $\times$ 12 / 7.6
$\beta_r\ /\ \beta_z$ max.	m	2.5 / 4.5
$\nu_r\ /\ \nu_z$		3.7 / 1.3
$B_D\ /\ B_F$	T	0.2-0.78 / 0.5-1.63
gap	cm	23.2 - 4.2
RF swing	MHz	1.5 - 4.5
voltage p-to-p	kV	2
rep. rate	Hz	250



Next FFAG beam : 2005

ADS/Reactor experiment facility, in construction at KURRI Institute
150 MeV / 100 μA

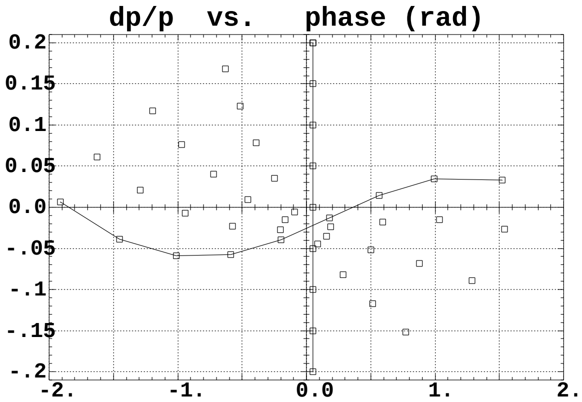


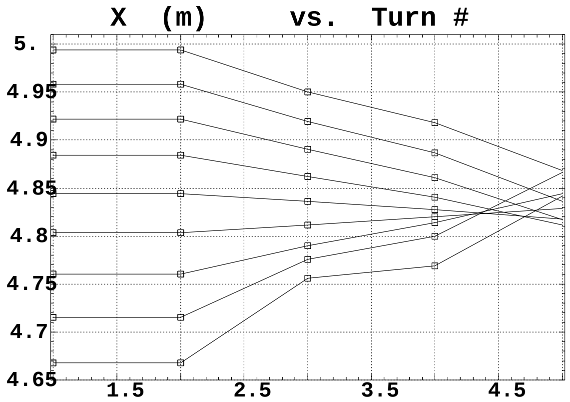
PRISM : Program started 2003, commissionning 2007

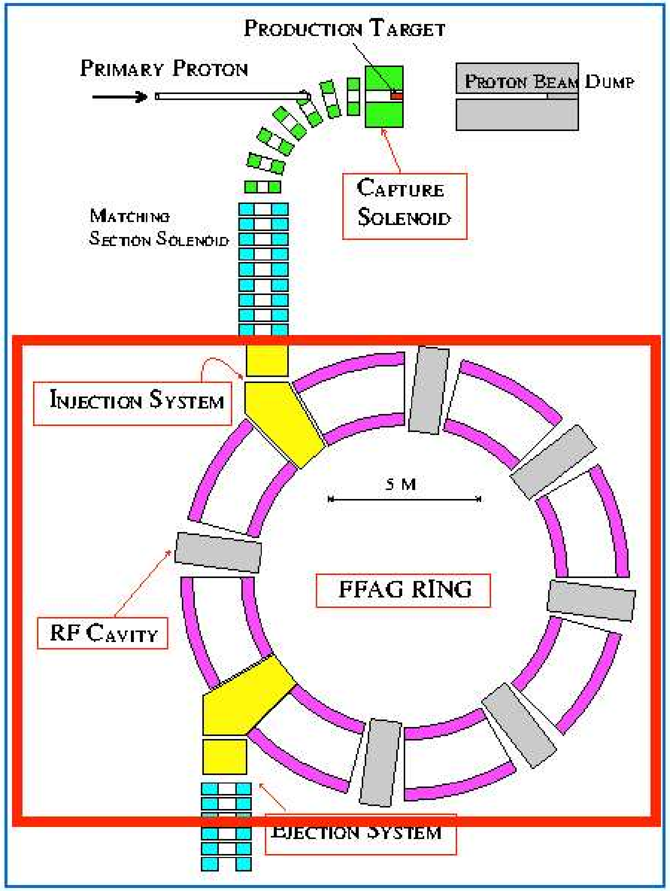
FFAG used as phase rotator, for momentum compression

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

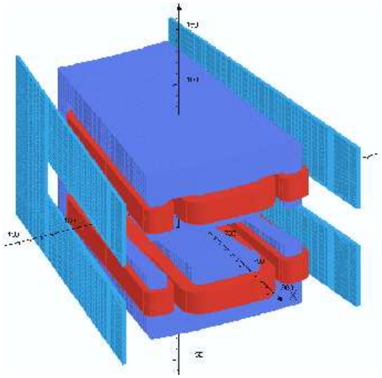
- DFD lattice 14t triplet yoke, 120 kW/triplet
- K, B_F/B_D variable $\rightarrow$ quasi-decoupled ν_x, ν_z adjustments
- H / V apertures : 1 / 0.3 m
- acceptance : 4 π cm.rad $\times$ 0.65 π cm.rad
- RF : 5-gap cavity, 33 cm gap, ≈ 2 MV/turn

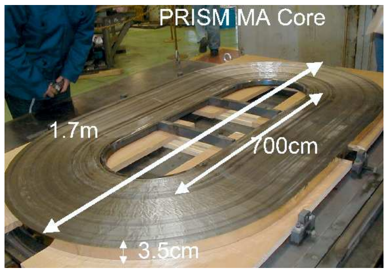






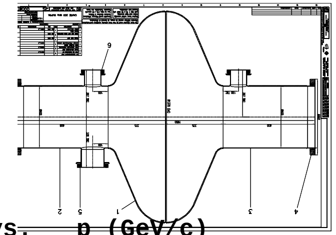
- Optics design : large acceptance achieved
- Magnet design : completed, $\xi = 0$
- RF system : more than 160kV/m at 5MHz expected
- difficult task : injection & extraction



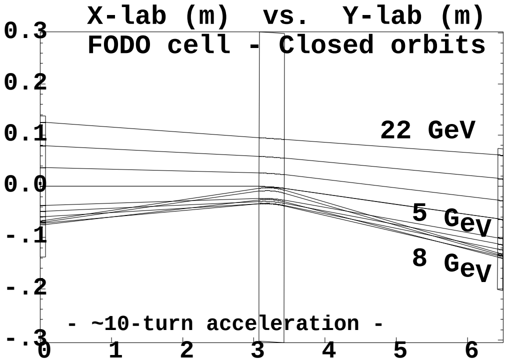


3 Non-scaling FFAGs, linear optics

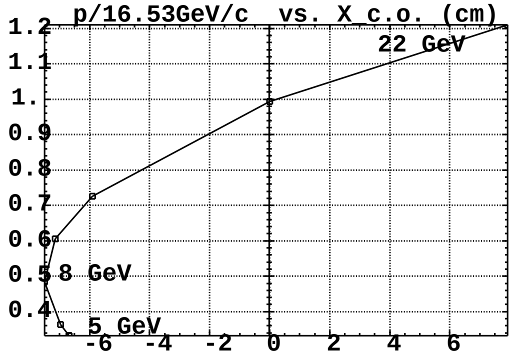
- New concept, introduced in the late 90's, for muons : **synchrotron-like cell - ! linear optical elements - & fixed fields**
- **Orbit position** moves in the course of acceleration, and **tunes change** unlike "scaling" FFAG
- Compared to RLA's : more turns hence less RF ; FFAG rings (2-3) are in smaller # than RLA arcs ($2 \times 4 - 5$ pass)



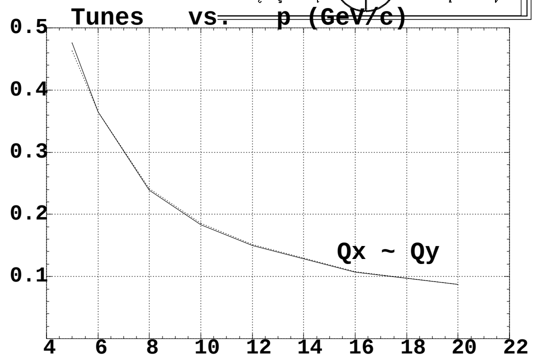
Typical (early) data. 6→20 GeV, 314 Cells, C≈ 2 km, B<6 T, B'<80 T/m, 10-20 MV/cell :



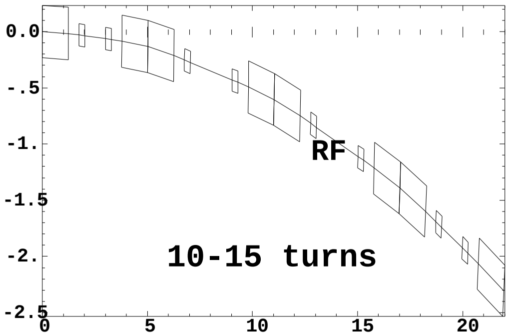
FODO (QF-O-BD-O) (%$\delta p/p,\ \eta$,...)



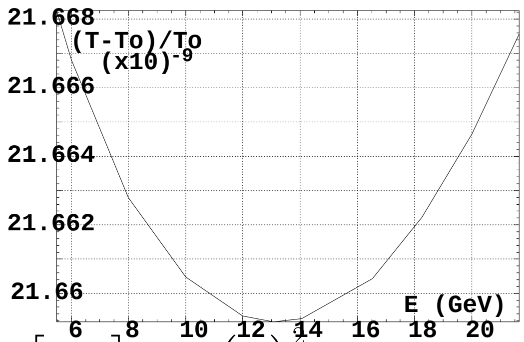
small $D_x,\ x_{co}$ reduced $-8/+8$ cm



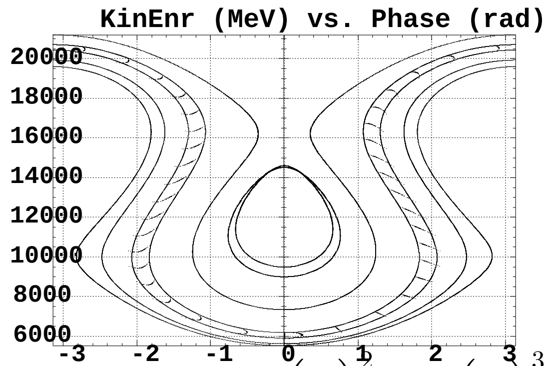
$\nu_{x,z/Cell}$ decrease: $0.5^- \ \to 0^+$



FDF (O-QF-BD-QF-O)



$\frac{\delta TOF}{TOF} \approx \left[\eta_0 \frac{\delta p}{p}\right] + \eta_1 \left(\frac{\delta p}{p}\right)^2$ ≈parabolic



$H \approx \sin^2 \pi\phi + [a \left(\frac{\delta p}{p}\right)^2] + b \left(\frac{\delta p}{p}\right)^3$

Linear, non-scaling optics induce a series of consequences :

- **large acceptance** (≈ 3 cm) ← linear fields. **Large momentum acceptance** $\Rightarrow$ prone to less (no ?) cooling
- **rapid acceleration** ($\approx 2-3$ E gain over ≈ 10 turns) ← high freq./$\vec{E}$ RF, near-crest ← small δTOF over E span
- **reduced circumference** (hence μ decay loss) compared to "scaling" ← circumf. factor $R/\rho < 2$
- **magnets have reasonable size** ← reasonable horizontal beam excursion ← small D_x

non-scaling FFAGs (cont'd) :

In practice,

- tens of cells cause **Xing of forests of integer and $\frac{1}{2}$integer resonances.**

This has harmful effects on beam transmission, that needs investigation

- **crossing is fast** though, this should result in not too stringent tolerance on alignements and field defects - needs more investigation

- **longitudinal motion is strongly non-linear**. Expected momentum acceptance in 1-2 eV.s range - needs more investigation.

Main conclusions, in present state of design optimisations :

- **costs :** above 5 GeV, non-scaling linear FFAG yield lower cost/GeV than RLA.

below 5 GeV : needs further investigation.

- **a new muon acceleration scheme** has been produced, RLA + non-scaling FFAG [NuFact04] :

- **muon rate :** of the order of $\boxed{0.3\ \mu/p_{20GeV range}}$

Beam from cooling/pre-acceleration

$\Downarrow$

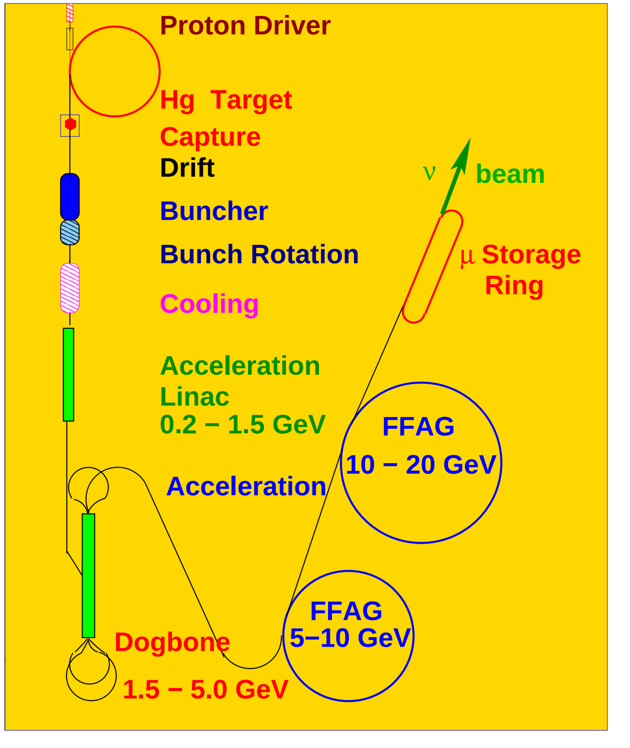
dogbone RLA $[1.5 - 5\ \textbf{GeV}]$

$\Downarrow$

non-scaling FFAG $[5 - 10\ \textbf{GeV}]$

$\Downarrow$

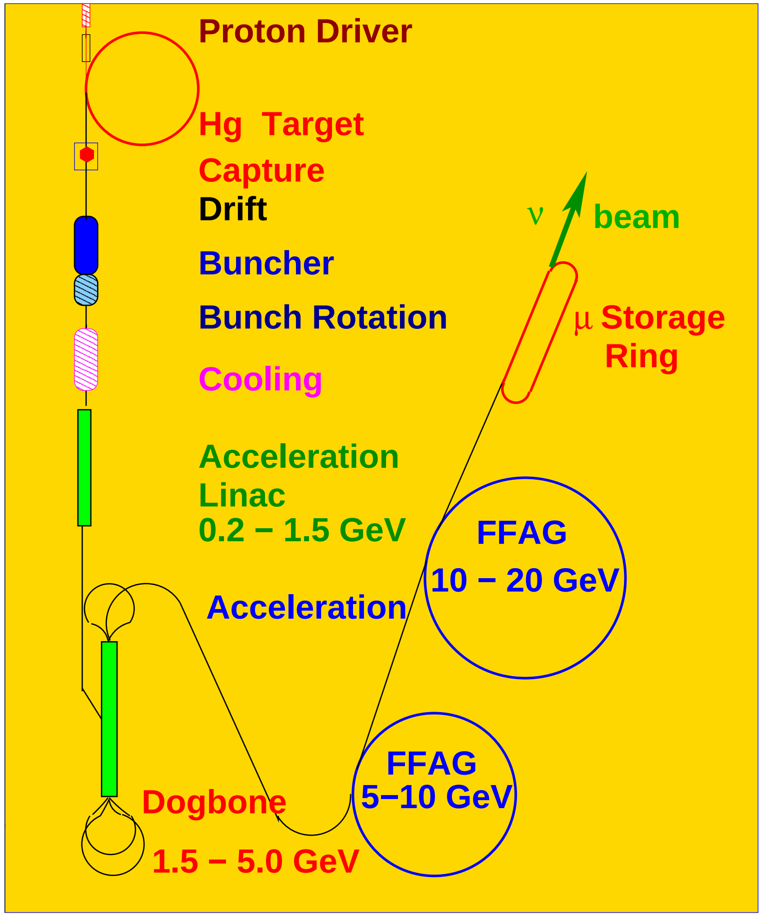
non-scaling FFAG $[10 - 20\ \textbf{GeV}]$



"There is no scheme with 3 FFAGs at this point. [SB]

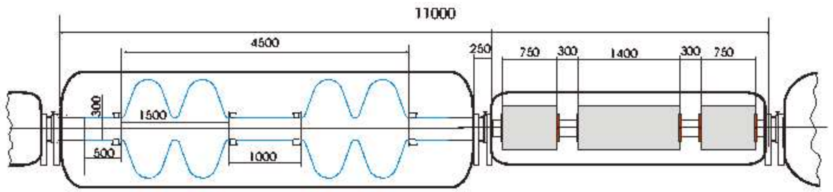
Low energy FFAG case (2.5 → 5 GeV) :

- Present 2.5→ 5 FFAG cost/GeV is comparable to the Study-II 2.5→20 cost/GeV.
- No good costing study concerning 1.5→ 5 GeV RLA
- No good costing study concerning RLA + 2.5→ 5 GeV FFAG stage. Might still be cost effective ?



Typical FFAG lattice data :

Energy	(GeV)	2.5→5	5→10	10→20
No. of turns		**6.0**	**9.9**	**17.0**
No. of cells		64	77	91
D length	(cm)	54	69	91
D radius	(cm)	**13.0**	**9.7**	**7.3**
D pole tip field	(T)	**4.4**	**5.6**	**6.9**
F length	(cm)	80	99	127
F radius	(cm)	**18.3**	**14.5**	**12.1**
F pole tip field	(T)	**2.8**	**3.6**	**4.4**
No. of cavities		56	69	83
RF voltage	(MV)	**419**	**516**	**621**
Circumference	(m)	246	322	426
Decay	(%)	6.4	6.8	7.7
Total cost	(PB)	71.6	77.5	88.9
Cost per GeV	(PB/GeV)	**28.7**	**15.5**	**8.9**



Dogbone :

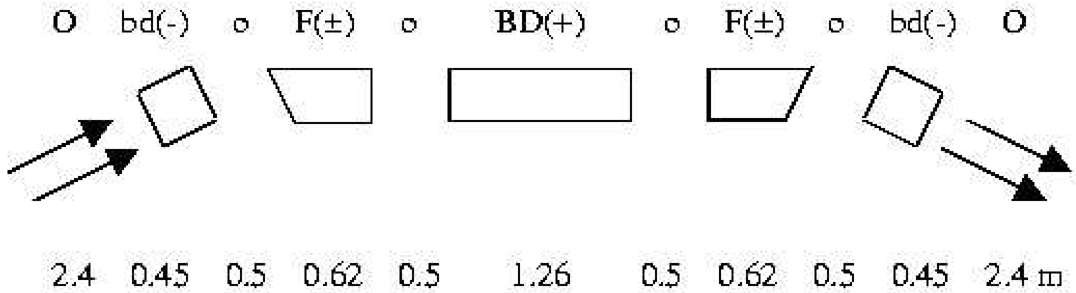
1 GeV linac, 3.5 pass. 200 MHz SCRF.
Acceptance: 3 cm / 0.05 eV.s, norm $(\delta p/p = \pm 17$%, bunch length=$\pm\lambda_{RF}/4)$.

4 Isochronous lattice, non-linear optics

A non-linear, non-scaling type of FFAG, “non-linear cyclotron”.

It has the advantage of optimum, on-crest acceleration.

Ex.: lattice for 8 to 20 GeV / 16 turns / 123 cell ring.

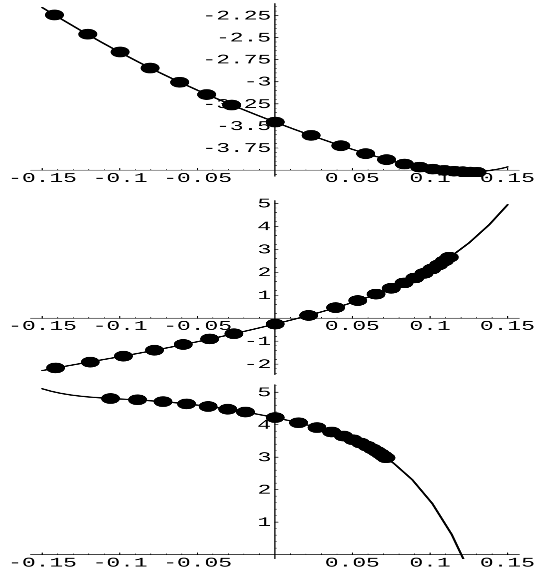


$$B_{bd}(x) = -3.456 - 6.6892\,x + 9.4032\,x^2 - 7.6236\,x^3 + 360.38\,x^4 + 1677.79\,x^5$$
$$B_{BF}(r) = -0.257 + 16.620\,r + 29.739\,r^2 + 158.65\,r^3 + 1812.17\,r^4 + 7669.53\,r^5$$
$$B_{BD}(x) = 4.220 - 9.659\,x - 45.472\,x^2 - 322.1230\,x^3 - 5364.309\,x^4 - 27510.4\,x^5$$

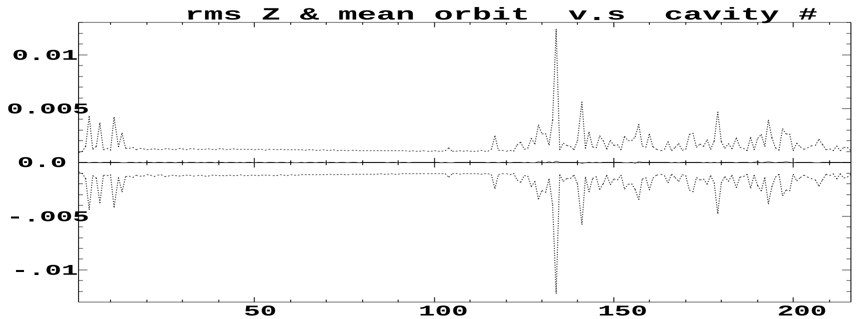
Possibility of insertions, with the adavntages of
1. reduced ring circumference,
2. easier injection and extraction,
3. space for beam loss collimators,
4. RF gallery extending only above the insertions, not above the whole ring,
5. 4-cell cavities usable, thus reducing, by a factor of four, the total number of rf systems.

A remark on 6-D tracking tools :
Strong need of performing codes for end-to-end simulations

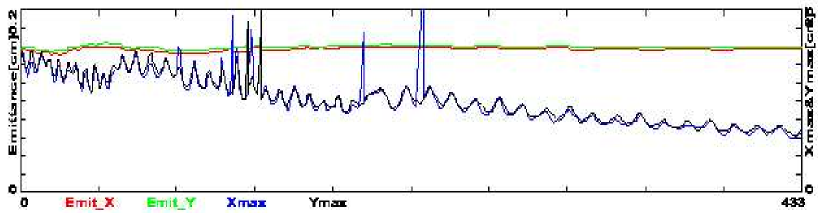
Magnetic field in bd, BF and BD.



Resoannce crossing :
rms beam size from 8 GeV to 20 GeV :



Note, similar preoccupations :
rms beam size in US-StudyII preaccelerator



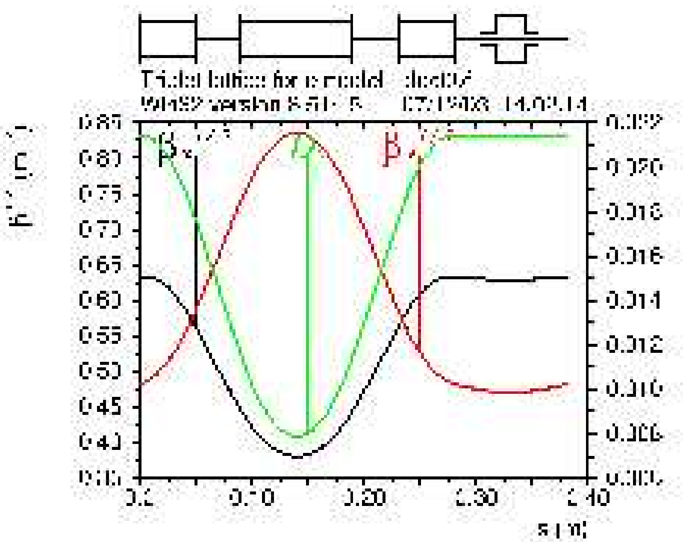
5 Conclusion : an e-model of a muon non-scaling FFAG is needed

"Since no non-scaling FFAG has ever been built, there is interest in building a small model which would accelerate electrons and demonstrate our understanding of non-scaling FFAG design. "

[Review of Current FFAG Lattice Studies in North America, JS Berg et als, 2004]

Goals for an electron model :

- resonance crossing
- multiple fixed-point acceleration
- input/output phase space
- stability, operation
- error sensitivity, error propagation
- magnet design, correctors
- diagnostics



Typical - not the most recent, though - parameters of an e-model of a muon linear non-scaling FFAG

Energy	*MeV*	10 to 20
number of turns		5 to 11
circumference	*m*	17
lattice		FDF
tune variation		$<$0.5
number of cells		45
cell length	*m*	0.38
RF drift length	*cm*	10
CF magnets:		
- length F/D	*cm*	5 / 10
- field F/D	*G*	375 / 107
- gradient F/D	*T/m*	6 / -5
- apertures	*cm*	1.2$\times$1.8
alignement tolerances		
gradient tolerances		
length variation	*rel.*	$2\ 10^{-3}$
RF frequency	*GHz*	3
peak RF voltage	*kV*	$<$80
h		171
RF power	*kW*	$<$1.5
max. I (beam loading)	mA	100

Many more details on Friday :

Geberal talk

scaling, non-scaling, isochronous FFAGs - design, beam dynamics, components

electron model

Thank you for listening