The acceleration of muons in the neutrino factory *NuFact05/Plenary*

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This paper first gives a brief recall, on the one hand, of the status of RLA based muon acceleration designs and of the major reasons that have motivated, in the US and in EU, the exploration of alternative ways of muon acceleration, and on the other hand, of the fixed field synchrotron (FFAG) based Japan NuFact design. This is followed by an overview of the most recent activities regarding the alternative technique of FFAGs, their promises, and the present goals of the research in this domain.

1. Introduction

Muon acceleration in the neutrino factory profits from modern accelerator technologies, that should permit in a near-future the building of a facility capable of bringing intense beams - in the 10^{20-21} muons/year range, to multi-GeV energies - in the 20-50 GeV range.

Various muon acceleration methods have been investigated, and have yielded different installations ; this will be reviewed in the following (Sections 2, 3). On the other hand, the accelerator community is now particularly concentrating on the method of FFAGs, and bringing new, modern ideas and concepts in the field. The "why" and "how" of that will be addressed in this paper (Sections 3, 4), as well as the consequences in matter of plans for future (Sections 4, 5).

2. The pre-FFAG era : RLA based designs

Linac acceleration presents the essential property of allowing fast acceleration, in a short distance, thanks to the use of high gradient / high frequency RF systems, compatible with the short rest lifetime of muons - $2.2\,\mu$s, thus ensuring a high transmission - typically, more than 80% at an average gradient of 5 MV/m. In regard with the large muon beam phase-space, superconducting Linacs also offer a substantial geometrical acceptance, owing in particular to the large iris of the ~200 MHz RF cavities, and the possibility of accelerating trains of bunches, all properties which translate into 6-D acceptance performance.

Three recirculating Linac accelerator (RLA) schemes have been produced, based on ≈200 MHz/10 MV/m SCRF, namely :

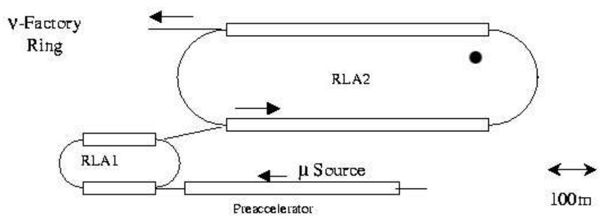


Figure 1. US Study I, the muon RLA concept. Following muon beam capture/bunching/cooling downstream of the production target, the pre-acceleration starts around 1.4 GeV, up to 3.4 GeV, and is followed by 8 and 50 GeV RLAs. Muon decay rate in the storage ring : $2\,10^{19}$/year/MW per straight.

US NuFact designs :

The US Study I, in 2000 [1] (Fig. 1), based on Linac pre-acceleration followed by two RLAs that bring the muon beam up to 50 GeV ; a follow-on, Study II, in 2001 [2] (Fig. 2), mostly, from the point of view of the acceleration, a lower energy (20 GeV) version, using a single RLA ; and, in 2004, an update, Study IIa [3], addressed in Section 4.1, which benefits in particular from cost-effective approaches, allows both signs of muons, and first sees the introduction of FFAGs in a combined Linac/RLA/FFAG acceleration scheme.

EU NuFact :

A design produced in 2004, 50 GeV top energy,

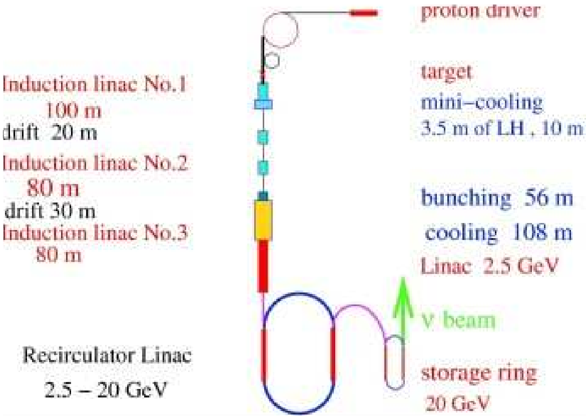


Figure 2. US Study II layout. Muon beam structure : a train of six bunches spaced 20 ms (hence target and accelerators rep. rate of 50 Hz), 3 ns bunch length at origin (target), rep. rate 2.5 Hz to be upgraded to 5 Hz. Muon bunches undergo 200 MHz "micro-bunching" (about 60 sub-bunches) prior to launching in the acceleration chain. Muon decay rate : $1.2\,10^{20}$/year/MW per straight.

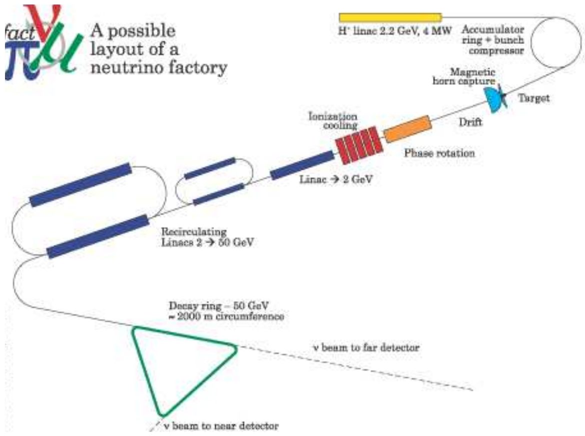


Figure 3. The CERN NuFact layout. Muon beam structure : $3.2\,\mu$s long trains of 140, 23 ns spaced bunches (44 MHz structure), at a rep. rate of 50 Hz. 1 ns bunch length at origin (target). Bunch-to-bucket operation : next to capture/phase-rotation/cooling, each muon bunch occupies a 220 MHz Linac RF bucket. 50 GeV top energy reached in three stages : Linac up to 3 GeV, followed by 3-11 and 11-50 RLAs. Muon rate : 10^{21}/year in the storage ring.

based on the acceleration of muons by a two-stage RLA system [4], and operating following a bunch-to-bucket mode (Fig. 3).

Amongst other conclusions, these feasibility studies are admitted to have "demonstrated technical feasibility (provided the challenging component specifications are met), established a cost baseline, and established the expected range of physics performance" and to have shown that "progress is still needed [...] towards optimizing the design, developing and testing the required accelerator components, and significantly reducing the cost" [3].

Nevertheless the cost of the NuFact installation is very high with the muon accelerators representing about a third of it, and the possibility that "FFAG rings could be also considered" [2, page 6.2], as a cheaper solution, already arises in the US Study II.

3. Japan NuFact. FFAG R&D

In 2001 Japan proposed a NuFact based on the JPARC 50 GeV proton installation, and on the capture and acceleration of the muons to 20 GeV by scaling FFAGs (Fig. 4) [5]. Acceleration in the high energy regime uses high gradient (in the 10 MV/m range), low frequency (5-25 MHz) RF, and is based either on huge-bucket method, with injection at the bottom and rotation upward at the manner RF manipulation in the PRISM experiment (see below), or, alternatively, on the use of frequency modulation. The FFAG method yields large transverse acceptance (on the order of $3\,\pi$ cm), large longitudinal acceptance (1.5 eV.s), and reasonably fast acceleration (1 MV/m on average), resulting in about 50 % muon survival.

The interest of the FFAG method is in its being rather compact (in particular if using SC magnets in the higher energy rings), potentially simpler

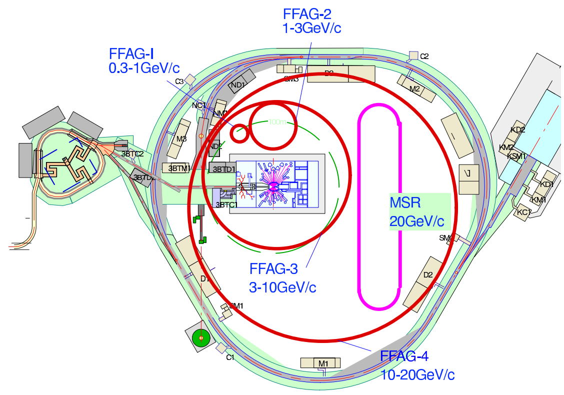


Figure 4. Japan NuFact layout. Proton driver : JPARC, 50 GeV ; phase I at 0.75 MW : rep. rate 0.3 Hz, $3.3\,10^{14}$ ppp, 8 bpp, upgradable to 4 MW. The first FFAG ring (0.2-1 GeV) assures muon bunch capture at the exit of the pion decay channel ; 20 GeV is reached in three more stages (1-3, 3-10 and 10-20 GeV). Muon decay rate in the storage ring : $2\,10^{20}$/year/MW per straight.

(hence cheaper), while in addition avoiding the cooling stages proper to Linac based installations.

Extensive R&D programs on scaling FFAGs have been pursued in Japan. They comprise, amongst other RF and component studies, the building of a proof of principle, 500 keV proton machine (Fig. 5) [5, App. C], which was followed by a larger, 150 MeV one [6], both based on a radial sector DFD triplet, which presents amongst other interests, that of providing reasonably long drifts, and the possibility of sensibly decoupled horizontal and vertical tune adjustment. These two machines proved in particular the feasibility of ultra-fast cycling, rep. rate in the kHz range, by means of high gradient RF systems based on special magnetic alloy cores [7].

This is now followed by the prototype ADS/Reactor experiment facility in construction at the KURRI institute, Kyoto (Fig. 5) [8].

The first muon FFAG will be the PRISM experiment (Fig. 6), a 2003-2007 program [9]. The lattice is based on a DFD triplet similar to the KEK FFAGs design, and comprises 10 cells. This FFAG is intended for muon bunch phase rotation aiming at momentum spread compression, from 68 MeV/c±20% down to ±5% in 6 turns, in view of the use in a muon beam physics facility. Remarkable features of PRISM are its 2 MV/turn RF system, and its challenging injection and extraction systems, a benchmark towards NuFact accelerators.

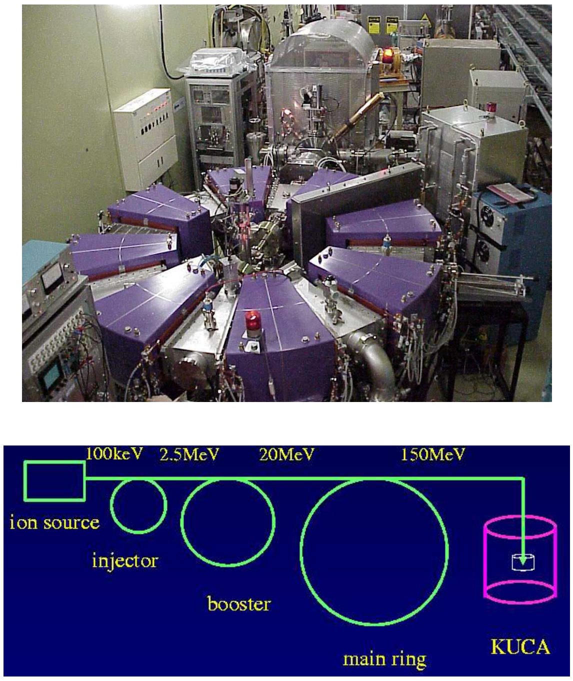


Figure 5. Top : The first proton FFAG ever built, the POP scaling FFAG at KEK. 50-500 keV, rep. rate 1 kHz. First beams 2000. A prototype of the muon beam manipulation machines. Bottom : A scheme of the ADS/Reactor experiment facility, in construction at KURRI Institute. 150 MeV / 100 μA proton beam, acceleration in three stages (0.1-2.5, 2.5-20 and 20-150 MeV). The first FFAG is of the spiral type, the next two are based on radial DFD triplet lattice.

4. Non-scaling FFAGs

A new FFAG optics concept has been introduced in the late 90's, for muons [10] : it uses

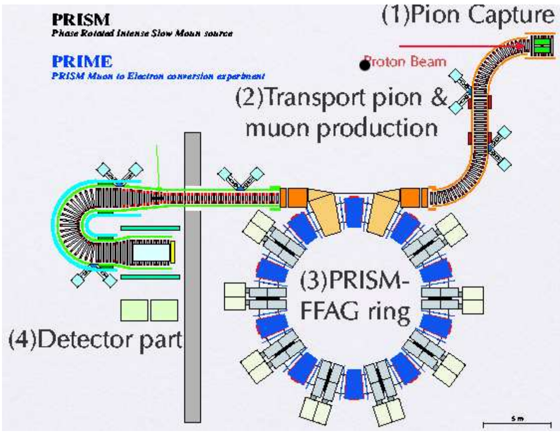


Figure 6. PRISM, the first muon FFAG, shown placed at the end of a muon collect channel.

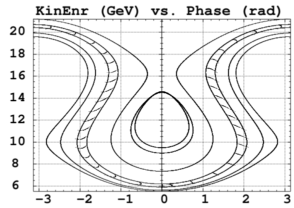


Figure 7. Longitudinal phase space, characteristic of the rapid acceleration in a linear, non-scaling FFAG. The particle bunch (visible turn after turn along the S-shaped channel) is accelerated from injection to top energy in a few turns (right-half of the figure, that also shows the symmetric behavior - deceleration - on its left-half).

synchrotron-like cell, i.e., only linear optical elements, with fixed fields. Hence, orbit position moves in the course of acceleration, and tunes change (by contrast with scaling FFAG) due to the change in beam rigidity.

Compared to RLAs, these "linear, non-scaling FFAGs" allow more turns, and hence less RF, and in addition the FFAG rings are in smaller number (2-3) than the arcs in RLAs ($2 \times$ 4-5 passes)

Linear, non-scaling optics induce a series of consequences as, (*i*) large transverse acceptance due to the linear fields, and in momentum due to the small dispersion function, up to the point to now question the necessity of cooling, (*ii*) rapid acceleration (energy gain of 2 to 3 over of the order of 10 turns), due to high frequency/high gradient RF and near-crest acceleration (Fig. 7), (*iii*) reduced circumference (hence muon decay loss) compared to scaling FFAGs, (*iv*) reasonable size magnets, due to the limited horizontal beam excursion.

There are drawbacks to the method, such as strongly non-linear longitudinal motion, and resonance crossing during acceleration. This is addressed in the last Section.

4.1. US Study IIa

Preliminary conclusions have been drawn from these works, in the present state of design optimizations : (*i*) linear FFAGs yield lower cost/GeV than RLA, above 5 GeV, and possibly below, this needs further investigation, (*ii*) a new muon acceleration scheme has emerged, US Study IIa, combining Linac, RLA and non-scaling FDF-lattice FFAGs [3] (Fig. 8). Typical parameters of the FFAGs are given in the Table below.

Energy	(GeV)	5→10	10→20
No. of turns		9.9	17.0
No. of cells		77	91
Circumference	(m)	322	426
D/F length	(cm)	69/99	91/127
D/F radius	(cm)	9.7/14.5	7.3/12.1
D/F pole field	(T)	5.6/3.6	6.9/4.4
No. of cavities		69	83
RF voltage	(MV)	516	621

The acceleration is based on 201 MHz SCRF. 3 πcm/0.05 eV.s acceptance is obtained (twice the transverse acceptance in Study II). Higher energy could be attained using additional FFAG rings.

4.2. Isochronous FFAG

Isochronism to high order allows on-crest acceleration, like in the cyclotron regime. This type of FFAG has been devised recently [12]. A current design is based on a 5-magnet cell using 3 differ-

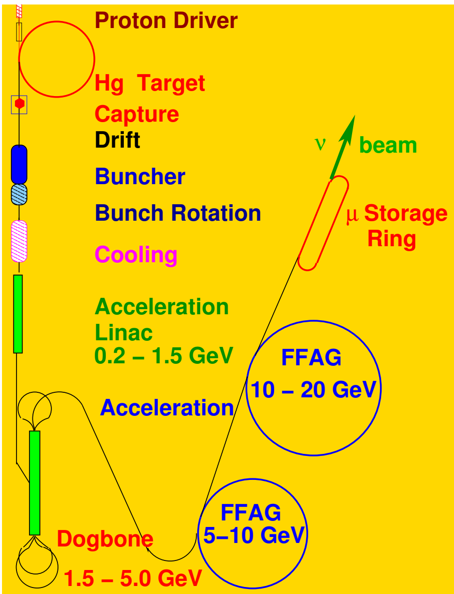
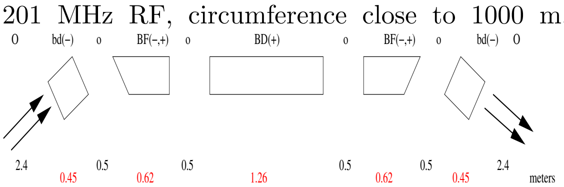


Figure 8. US Study IIa. 1.5 GeV SC Linac, followed by a 3.5-pass 5 GeV dogbone SCRF RLA [11] and two FDF-lattice FFAGs, 5-10 and 10-20 GeV. Muon beam structure as in Study II (Fig. 2). muon rate $\approx 0.3\mu/p_{20GeV range}$, twice that of Study II.

ent types of combined multipole magnets, Figure below. The cell acts as a DFD triplet at low energy and as an FDF triplet at high energy. Using two families of cells allows in addition designing a ring with insertions. The horizontal tune varies ($\lesssim 0.15$/cell), whereas the vertical tune is about constant. A 8-20 GeV muon ring as been designed this way, acceleration in 16 turns using 201 MHz RF, circumference close to 1000 m.



The isochronous FFAG with insertions has the following advantages: optimum, on-crest acceleration, resistive beam loading, the flexibility of insertions (injection, extraction, collimation), fewer RF systems by the use of 4-cell cavities, and no crossing of integer or half-integer vertical betatron resonances during acceleration (by contrast with linear FFAGs).

5. Electron model

A proof-of-principle of non-scaling FFAGs is needed, with the goal of demonstrating in particular the viability of the concepts of

- rapid acceleration : the longitudinal motion is strongly non-linear, momentum acceptance in the eV.s range expected,
- resonance crossing : muon FFAGs are built from tens of cells, which results in the crossing of tens of integer and half-integer resonances in the course of acceleration (due to the tune change), this has harmful effects on beam transmission, and in particular imposes constraints on field and alignment defects.

These considerations have motivated the emergence of the EMMA project of an electron model of a non-scaling FFAG [13].

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