Report of Working Group I: FFAGs for Muon Physics

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INTRODUCTION

Much of the April 2004 *to do list* relating to FFAGs for muon physics, from the workshop held in Vancouver B.C., has been accomplished; either between the workshops or at this meeting. Activities were focused mostly on the few-MeV electron model of a multi-GeV muon accelerator intended for a Neutrino Factory[1] or Muon Collider; the PRISM[2] FFAG for a lepton-flavour violation experiment was also discussed.

Communications

The public relations campaign to win community recognition for the importance of FFAG accelerators in diverse applications including proton drivers, muon acceleration, and cancer therapy, began with a popularising article in the CERN Courier[3], invited talks[8, 4, 5, 6] at the 2004 EPAC and Cyclotron meetings; and continues with this first **AIP** proceedings dedicated to FFAGs, and the promise of papers[7] invited to the 2005 PAC.

Isochronous semi-scaling FFAG

The novel isochronous semi-scaling FFAGs presented by G. Rees and H. Schönauer constitute possibly the most exciting development at this workshop. The classical scaling FFAGs have constant betatron tunes, and make few restrictions on the orbit period versus momentum. The linear nonscaling FFAGs have large negative chromaticity; and, though they try to minimize the time-of-flight variation, make no attempt at true isochronism. Both new semi-scaling machines offer near perfect isochronism; the Rees machine has moderate positive chromaticity, and Schönauer's lattice offers also the promise of near zero chromaticity.

Cost optimization of nonscaling muon FFAG

Though the working group failed to establish a set of technical criteria by which preferred lattices can be selected from the the various competing designs for the muon and electron non-scaling FFAGs, progress was made on the *de facto* arbiter - namely cost. By including externalities such as the cost to the experimental detector of muon decay losses, J.S. Berg has bolstered our confidence in the small-ring, high-field versions of the muon FFAG as representing the cost minimum.

Progress with electron model FFAG

There was a variety of progress on the electron model. First, Daresbury Laboratory, U.K., has identified itself as a potential host for the demonstration machine; and the working group welcomed representatives of the U.K. Council for the Central Laboratory of the Research Councils (CCLRC) R. Edgecock and C. Prior. Second, progress was made on defining a machine alignment and beam diagnostic strategy for the electron model, and in assigning appropriate instrumentation to that task. Third, and crucial to the success of the muon nonscaling FAFGs, two full-6D tracking studies of resonance crossing in the electron-model were reported at this workshop. The studies, which are (more or less) in agreement, lead to the setting of tolerances on magnet alignment and gradient errors, and give confidence that integer and half-integer resonances may be crossed. However, the alignment tolerances may prove challenging. No progress was made with concepts for, or detailing of, the injection and extraction kickers and layout; this should be given high priority at the next meeting.

ISOCHRONOUS SEMI-SCALING FFAG

In an isochronous ring, the variation of speed with momentum is carefully balanced against the change in path length, so that orbit period is independent of momentum - for matched closed orbits. Isochronism guarantees perfect synchronism with fixed radio-frequency electric fields responsible for acceleration, and has the benefit that the particle beam rides the crest of the waveform thereby receiving the maximum possible energy gain. The always-resistive loading of the rf cavity is also seen as an advantage, because there is no reflected power.

The new lattices utilise turn-to-turn isochronism; that is to say a select few reference momenta and respective orbits are made perfectly isochronous. About each of these orbits one may set up a dispersion function, and calculate the time-of-flight (ToF) for a small bundle of the off-momenta. In the Rees lattice, the linear ToF variation versus momentum (about each of the reference momenta) is set to zero, giving (almost) exact isochronism – that is γ-transition equals γ-beam for the reference orbits. In Schönauer's version, less attention is paid to specifying precisely the momentum compaction at each of the reference orbits but nevertheless the deviation from isochronism is very small.

Note, in the linear nonscaling FFAG the momentum compaction varies considerably in magnitude and sign; and so designers have given up working with γ-transition in favour of specifying the time-of-flight versus momentum curve. The designers of semi-scaling lattices are recommended to follow suit. It is the deviations from isochronism that will set limits on the longitudinal dynamics, and these are easier understood from the ToF than γ-transition.

Isochronism at relativistic energies is not possible in cyclotrons. The comparative miracle of isochronism in the semi-scaling FFAG is achieved by using a magnetic lattice with nonlinear elements in which the field and gradient (B_0, B_1) are specified on each of the selected reference orbits. Both lattices use cells that are reflection symmetric about their centres; Rees and Schönauer adopt 5- and 7-magnet cells, respectively, with 4 different magnet designs but the magnet geomtrey is simpler for the latter. Schönauer's lattice has the advantage of near zero chromaticity, but the Rees machine has the benefit of longer straights for more compact RF.

The potential for many-turn acceleration and greatly reduced installed rf voltage make the isochronous FFAGs very attractive. However, both lattices must be submitted to extensive particle tracking studies to identify whether the influence of nonlinear resonances is inconsistent with the very large transverse acceptance required for the intended muon application.

OPTIMIZATION OF NONSCALING MUON FFAG

From the 18th century to present times, economists such as Adam Smith and Milton Friedman have advocated the market approach to decision making, that is choice based on comparative cost. Berg and Palmer first introduced a cost model for muon FFAGs at the UCLA *Mini Workshop on Ring Coolers*, held in March 2002, and they have continued to refine that model. For example, the magnet model now includes the fixed costs associated with fabrication.

Studies with an early cost model revealed an asymptotic minimum favouring rings with a large number of cells, small bend angles and magnet apertures and weak fields. However, the large rings incur substantial muon decay loss and the low-cost lattice designs were inadvertently influencing the cost of the experimental detector which must battle with the compromised luminosity. Continuing with the connection to economic theory, this can be likened to transnational corporations externalising their costs by moving their production to locations where there are few environmental regulations. Realising this defect, Berg has internalised the marginal increase of detector cost with respect to muon decay loss. In the new model, there is now a clear minimum and it favours relatively small rings with strong bend fields; indeed the peak magnetic fields exceed those considered at the April 2004 workshop.

The cost model has still room for improvement. One may think to (i) include a measure of the operating costs in addition to the construction cost; (ii) consider the effect of FFAG aperture selection on the cost of muon cooling upstream; and (iii) quantify the cost of nonlinear emittance distortion so as to better inform the choice of the longitudinal acceleration parameters $a = (\delta E/\Delta E)/(\omega \Delta T)$ and $b = \delta T_2/\Delta T$. The usual reason to consider operating cost is to choose between room-temperature and cryogenic rf-cavities; but since that decision is already made in favour of superconducting rf, it is not clear where the influence will come. Some aspects of the longitudinal emittance issue were quantified (at this workshop) by Koscielniak in terms of dwell time, acceleration efficiency, time dispersion and the need to match eccentricity and orientation of the beam ellipse to the injection/extraction working points.

ELECTRON MODEL OF LINEAR NONSCALING FFAG

Purpose of the muon nonscaling FFAG

All schemes to produce intense sources of high-energy muons (neutrino factories, beta beams, muon colliders) require collection, rf capture, and transport of particle beams with unprecedented emittances, both longitudinally and transversely. In comparison with high-energy hadron facilities, the transverse emittance is a factor of 1000 larger in each plane, and the longitudinal emittance is 20-100 times larger even after bunching and phase rotation. These large initial emittances must be reduced or *cooled* both in size and in energy spread before the muons can be efficiently accelerated to multi-GeV energies; a factor 2.5 to 10 reduction per transverse plane for a neutrino factory and a factor of 1000 for a muon collider. Longitudinally, the degree of cooling differs depending on the acceleration method.

In a neutrino factory the limits to accelerating large-emittance beams determine the specifications which upstream systems must meet, particularly the cooling. The downstream storage rings and experiments are presently not the limiting constraint. Transverse cooling is preferable in any approach after collection and capture to avoid enhanced component apertures, power levels, and, hence, cost of acceleration systems. However, it is the choice of accelerator that determines the useful longitudinal acceptance and, therefore, also the degree of longitudinal cooling. Acceleration proves, then, a pivotal stage to develop in the path to this facility. To further complicate issues, acceleration must occur rapidly because of potentially heavy losses from decay.

Muons are created via the decay of pions, and pions are produced by directing an intense beam of protons on to a production target. The muon transverse emittance captured by the strong, large-aperture solenoid surrounding the target is roughly 16π cm-rad (full, normalized) at a momentum of 200 MeV/c; the momentum spread is $\delta p/p \approx \pm 20$ %. There follows a stage of (at least) modest ionization precooling in a dedicated channel (or possibly ring cooler). Adiabatic damping by acceleration in a single-pass linear *pre-accelerator* to energy 2.5 GeV leads to a reduction in *geometric* emittance by a factor of 12. This prepares the beam for injection into subsequent multi-turn accelerators with reasonable-sized component apertures. Both recirculating linac accelerators (RLAs) and FFAGs have been considered for acceleration beyond 2.5 GeV; several stages are needed with a factor 2-3 energy increase in each. The machine choice impacts the required level of cooling. Simple adiabatic damping during acceleration to 20 Gev (if the dynamics are adequately conserving) is sufficient for the final transmitted emittances to meet the requirements of the storage ring and experiment.

The RLAs have their merits but are challenged by the large emittances and, particularly, the large energy spread - limiting the recirculation to four passes. In recent designs, acceptance is limited to 1.5π-2π cm-rad (normalized) and $\delta p/p \approx \pm(5\text{-}10)$ %. Thus the incipient (200 MeV/c) emittance must be cooled by a factor of 8-10 transversely and at least 1.4-3 longitudinally before acceleration can be accomplished in an RLA designed for a Neutrino Factory.

Nonscaling FFAG designs exist with component apertures of 30-40 cm horizontal (20 cm vertical) that accept a 6.4π cm-rad emittance (full, normalized) at 2.5 GeV; and the relative momentum acceptance at injection energy is, practically, about ±14 %. The beam is anticipated to circulate roughly 10 times and is limited by slip between the bunches and the fixed rf. The component apertures are comparable to those of RLAs. Even with a lattice optimized for acceleration and cost, the FFAG scheme requires only a modest factor 2.5 transverse cooling prior to acceleration, and little or no longitudinal cooling. To fully realize the reduced cooling factor, however, the pre-accelerator must be capable of “linearly” accelerating both large transverse and large longitudinal emittances.

The reduction of transverse and the elimination of longitudinal cooling, involving transmission losses and further muon decay, and reducing the severity of general R&D issues associated design of advanced muon cooling channels, makes a persuasive argument[12] to adopt the nonscaling FFAG as the acceleration stage of a neutrino factory.

Purpose of the electron model

Though the variable-tune linear-field FFAG uses conventional linear magnetic elements, that are similar to those used in synchrotrons, these machines are intended to operate in a very novel way. Whereas the synchrotron increases the magnetic fields during acceleration, and typically tolerates a relative momentum spread $\ll 1$ %, the FFAG operates at fixed magnetic field with a range of *central* momenta spanning up to ± 50 % in $\delta p/p$. This has two consequences: (i) the transverse focusing strength falls with increasing momentum, leading to negative chromaticity; and (ii) the particle beam moves across the radial aperture, during acceleration, leading to a significant change in the orbit shape, which produces a quasi-parabolic time-of-flight variation. The first property leads to the crossing of many integer and half-integer betatron resonances; the chromaticity is about the natural value $(\delta\nu/\nu)/(\delta p/p) \approx -1$, but the momentum range is large. In a machine with fixed radio-frequency, the second behaviour necessitates acceleration within a rotation manifold, a bundle of serpentine phase-space paths linking injection to extraction, rather than the customary libration manifold of the pendulum oscillator (a.k.a. *rf bucket*). Both items constitute new domains for accelerator physics.

The purpose of the electron model is to demonstrate and investigate the novel acceleration features in a nonscaling FFAG that is a small fraction of the cost of the multi-GeV muon machine. Reducing the momentum by a factor 1000, that is to a few MeV, leads to electric and magnetic fields that are readily achievable with room temperature technology, and to a ring of a few metres radius - suitable for a small hall. In addition a small electron linac and source is required as injector. Thus far, an energy range of 10-20 MeV has been considered for the model.

Longitudinal investigation

The phase space is governed by the two parameters (a,b) introduced earlier. If the longitudinal emittance is small enough, then the combination of the energy variability of the linac and injection timing c.f. the ring rf phase, will allow a detailed probing of the phase space topology as parameters are varied. a, which is proportional to the energy gain per cell (δE), influences acceleration rate and is easily varied through cell voltage. $b = \delta T_2/\Delta T$ determines at what momenta is the rf synchronous with the orbit period, and influences the acceleration range. ΔT is the height of the ToF parabola, and T_0 is the reference cell transit time.

The main feature of the phase space is that for given b, the rotation manifold opens or closes depending on a. To vary b, either the machine circumference or the radio-frequency must be changed; the latter is preferred. The range $b = [0, \frac{1}{2}]$ implies a relative variation of period, or frequency, by $\frac{1}{2}(\Delta T/T_0)$ which amounts to roughly 5×10^{-4} in the electron model lattices. Thus arises the requirement to vary the klystron signal frequency and the cavity resonance frequency by $\simeq$ MHz about the $\simeq$ GHz centre. Widebanding of the klystron performance is achieved by stagger-tuning its output coupling cavities - at the expense of reduced efficiency and peak power. The cavities will probably have to be tuned mechanically.

Resonance investigation

To some degree the resonance crossing study is coupled to the longitudinal motion via *crossing speed*. The electron model will benchmark the emittance growth scaling law; and, ideally, the resonance driving strength and crossing rate should be independently variable. When $b = 0$, there is no lower limit to the crossing speed (proportional to a), but the momentum range is severely restricted. When $b \neq 0$ there is a wider variety of longitudinal phase space structure with which to perform acceleration but the serpentine-shaped rotation manifold closes off at low acceleration rate (small a). To thoroughly investigate resonance crossing, one must take advantage of the energy variability of the injector to set the initial momentum and thus working tune.

Host for electron model

A significant development since the April 2004 workshop is the enthusiasm of Daresbury Laboratory in the U.K. to consider hosting the electron demonstration model. Prior to this development, the Brookhaven Accelerator Test Facility[13, 19] was touted as a possible host. The possibility to realize the electron model is exciting and would reward the creativity and hard work of the last 3-4 years.

One among six initiatives of the Accelerator Science and Technology Centre (ASTeC) of the CCLRC, the Energy Recovery Linac Prototype (ERLP) is a funded project[10, 11] for an 8-35 MeV energy-variable superconducting linac based on TESLA[14] 1.3 GHz technology that will provide a test bed for the study of beam dynamics and accelerator technology important for the design and construction of a proposed 4th Generation Light Source (4GLS).

Radio-frequency

The possibility of adapting the electron ring to a 1.3 GHz injector was the cause for revisiting the choice of radiofrequency, nominally 2.9 GHz. In the muon FFAG, it is a necessity that every cell contain a 200 MHz rf cavity in order to achieve the roughly GeV per turn acceleration rate. The distributed rf concept is adopted also in the electron model to avoid strong discretization of the energy gain, leading to some 30 cavities. This has also the benefit of reducing coherent synchro-betatron oscillations.

The S-band (SLAC-style) solution uses a single klystron and a tree-like system of power dividers, waveguides and phase adjusters to deliver power (at the correct phase) to each of the 3 GHz cavities. The L-band solution is similar but could benefit from the *linear rf distribution* scheme intended for TESLA. The scope of discussion was widened to include an 850 MHz option where Inductive Output Tubes[15, 16] of few kW power drive an equal number of cavities; this eliminates many dividers and waveguides, and synchronization is achieved via a low-level rf signal. The group benefitted from consultation with Kazushi Hanakawa of *Mistubishi Electric Corporation*.

To give the freedom to choose the ring rf independent of that of the injector linac, it is proposed to operate the ring with a single electron bunch. This has also the benefit of easing the extraction/injection kicker requirements.

Regarding the radio-frequency, the choice is between three ugly sisters, there is no Cinderella. The IOT option is ruled out due to the cost of the replicated power supply for each tube. Neither the 1.3 or 2.9 GHz choices are ruled out.

Resonance crossing studies

The linear-field, variable-tune type of non-scaling FFAG will cross many betatron resonances of the transverse motion during the course of the few turns acceleration; and this is considered worriesome because of the potential to degrade the transverse emittances. However, there is the belief that if driving terms are small enough and crossing is fast enough, then there is insufficient time for the betatron amplitudes to grow. At the April 2004 workshop, R. Baartman reported formulae (based on Fresnel integrals) for crossing of a single resonance (1, $\frac{1}{2}$, $\frac{1}{3}$, etc)-integer. E. Keil presented a preliminary tracking study[9] of an electron model lattice with misalignments in April and at the 2004 EPAC. Nevertheless, it was perceived that mature and corroborative studies were needed. Three such investigations, one experimental and two computational, were reported at this workshop.

Experiment at PoP FFAG

Masamitsu Aiba (Tokyo Univ.) noted that the literature of experimental studies dedicated to resonance crossing in particle accelerators is very sparse, and that any addition is welcome. By making the *k*-value vary with radius, the scaling property of the KEK PoP[17] FFAG has been compromised in favour of betatron tune variations of $\delta\nu_H = .06$ and $\delta\nu_V = .03$. Allied with driving terms from the RF core and/or septum, this gives the opportunity to investigate crossing of the third-integer resonance $3\nu_H = 7$ at a variety of speeds dictated by the rf voltage; the effect is measured by beam size. There are two main conclusions: for given excitation, the change in beam size becomes undetectable at larger crossing speed; and the effect depends on the direction of crossing.

Particle tracking studies

Keil and Sessler reported 5-turn tracking studies of their doublet lattice performed with MAD. Misalignments drive orbit distortions (which may compromise aperture) and integer resonances; the distortions also lead to ToF variations which impact acceleration. The tracking results imply an upper bound for the errors of 30 μm r.m.s. gaussian distributed.

Machida's study is broader: to investigate alignment *and* gradient errors, and a variety of resonance crossing speed and drive strengths. However, a possible deficiency was to base emittance growth estimates on single-particle tracking. Gradient errors may drive half-integer resonances. As noted by Koscielniak, a full range of crossing speeds cannot be accessed without changing the radio-frequency; and that necessity is observed in the tracking using SIMPSONS. For succesful acceleration over 5-turns in the Trbojevic-Courant triplet lattice, Machida finds that alignment errors must be kept below 50 μm 100% for a uniform distribution; which is comparable with Keil's result. The gradient errors must be kept below 0.5%, and for example 0.1% is considered achievable at the JPARC[18] (formerly JHF).

Machine alignment

The positioning of the electron model magnetic elements has to meet the tolerances stated above. E. Keil and Hatoshi Hayano suggested strategies to meet these requirements based on experience at CERN and the KEK ATF[25], respectively. The ATF[21, 20] is a 1.3 GeV electron, racetrack-shape, damping ring with 2.9 GHz linac injector. The arc lattice is a minimum-emittance type composed of cells with F-quadrupoles and combined function magnets. The correction elements, steering bends and trim quads, are comparable in size to the main elements in the electron model. The proposed alignment strategy is:

- A single concrete slab for the entire ring.
- Support the vacuum chamber independently of the magnets, so that stresses from the former are not transferred to the latter.
- Each cell on a girder (a.k.a. strong back), or perhaps two cells on a support table.
- Align components on the girder, using a laser tracker and piezo actuators, in the measurement laboratory; 10 μm is achievable. Then move each girder into the ring on an air-pad transporter.
- Align girders using a central laser tracker; $<$ 50 μm is achievable.
- The laser tracker needs a clear line of sight to targets on all machine components; avoid introducing obstructions e.g. waveguides.
- To achieve better accuracy there is no substitute for beam-based alignment.

An example ATF support table is shown in figure 1. General issues of alignment have been addressed at the *International Workshop on Accelerator Alignment* (IWAA) series of meetings[23, 24, 26, 27]. The Laser Tracking Interferometer, or *laser tracker*, is widely available from the optical industry and has been used in accelerator alignment since 1994[28]. For example, the APS at Argonne, the CERN LHC, and KEK ATF have all adopted units from *Leica GeoSystems*[29]. The commercial units have accuracy of 20μm or better over a few metres. Beam based alignment[30, 31] relies on finding the response matrix from variation of individual quadrupole strength to beam position at monitors, and is extended[33] to the effect of steering elements.

Beam diagnostics

The proposed electron model is to be dedicated to accelerator physics experiments. In addition to providing the customary beam position monitorts (BPMs) for commissioning of the basic optics, additional equipment is needed to instrument the betatron resonance crossing studies and to explore the various longitudinal phase space manifolds. The transmission efficiency of the ring is measured by inegrating current transformers, of the Bergoz[35] type, in the injection and extraction channels.

Closed orbit

The closed orbit BPMs are of the button-type[36], and there are two per plane per cell. Given the 3 cm aperture, a resolution approaching 3 μm is possible with careful design; but this requires extreme care over low-noise electronics[37]. The BPMs will be used also to infer the beam momentum, as no spectrometer is foreseen. Turn-by-turn data acquisition, for possibly many turns, will be essential to disentangle the amplitude and dispersion optical functions since these vary during acceleration.

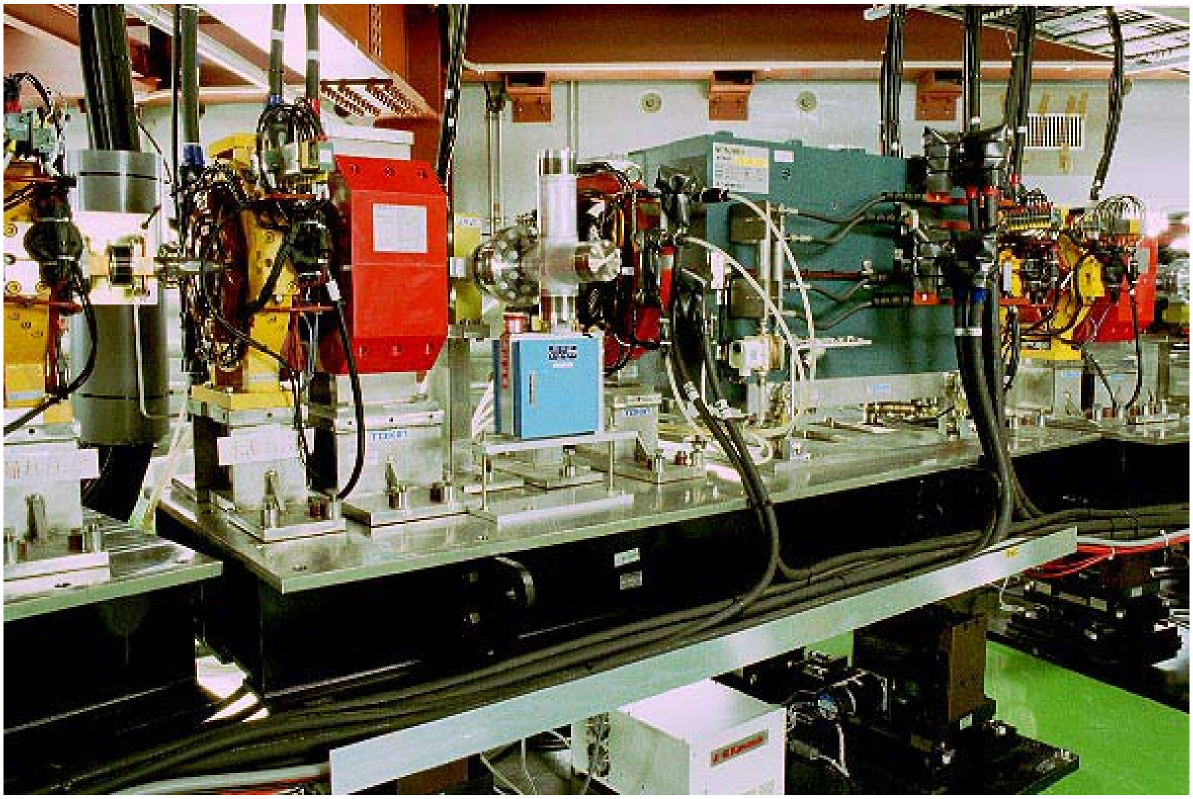

FIGURE 1. Support table for magnets in the arc sections of the ATF Damping Ring. Each table is for one combined-function dipole magnet (green), a defocusing quadrupole magnet (thin, red), a focusing quadrupole magnet (thick, red) and a sextupole magnet (yellow). A vacuum pump is also seen (blue). Small dipole magnets for beam orbit corrections and a beam position monitor are also implemented on each support table. In this photo the electron beam travels from the right to the left.

Emittance measurement

Transverse emittance measurement is crucial to the resonance crossing study; because this measurement is destructive, there is no alternative but to kick the beam out to an "emittance rig" in the extraction channel. The kick is uniform along the bunch and shall be programmable on any turn. The standard rig consists of a pepper-pot plate, fluorescent screen[22], CCD camera and image capture; data is acquired in a single shot. The 1.5 mm thick pepper-pot plate[38] with an array of 0.3 mm holes spaced by 3 mm used at the Argonne Wakefield Accelerator with 14 MeV electrons could be a useful model.

Longitudinal profile

The effect of acceleration on the electron beam will be inferred from the within-bunch time structure; a spectrometer for momentum measurement is not foreseen. The bunch occupies a small fraction of an rf wavelength. At either 1.3 or 2.9 GHz, the time structure is beyond the reach of a wall-current monitor - these have bandwidth up to a few GHz. Instead, a transverse deflecting cavity[34] and a fluorescent screen, installed in the extraction channel, are used to give a streak-camera-like operation in which the time dependence is converted to a position dependence. The cavity gives a transverse delection which varies along the bunch; such systems are used at SLAC[32, 39] and ELBE[40].

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