Session F: FFAG and other advanced accelerators and technologies

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INTRODUCTION

This session was purposefully chosen to include a wide variety of topics; to encourage interdisciplinary communication. There were four broad themes: advances in longitudinal manipulations, success and challenges for fixed-field alternating-gradient (FFAG) accelerators, applications of lasers, and progress in superconducting technology. In addition to their own intrinsic qualities, the workshop classed these technologies as either *mature*, available today; or *advanced*, available soon. As a generality, the session benefitted from an excellent series of talks with the varied concepts very clearly expressed; and the convenors express their gratitude to the speakers.

- Ken Takayama (KEK) - Induction synchrotron;
- Kiyomi Seiya (FNAL) - Slip-stacking and barrier RF;
- Sandro Ruggiero (BNL) - Challenges for FFAGs;
- Hong Qin (PPPL) - R& D for HEDP & WDM;
- Julien Fuchs (LULI)- High brightness hadron source and acceleration by lasers;
- Sergei Kondrashev (ITEP) - Direct plasma injection ion source;
- Isao Yamane (BNL) - Laser stripping of H^0;
- Carsten Muehle (GSI) - Fast-pulsed s.c. magnets;
- Michael Kelly (ANL) - SC spoke cavities.

LONGITUDINAL MANIPULATIONS

Induction Synchrotron

Takayama explained his novel concept[1] of the *induction synchrotron* and experiments at the KEK-PS to prove this technique. The idea is to separate acceleration from confinement, and to achieve this by using pulsed, rectangular waveforms: a long flat top for acceleration, and narrow pulses of opposite polarity (barriers) for confinement. A conventional, sinusoidal RF-type waveform is *not* used; instead a high-power pulse generator drives an *induction cell*[3], which is essentially a Magnetic Alloy cavity with direct inductive coupling by a loop wound around the core. One group of cells is dedicated to acceleration, and another to generating the barrier pulses. One benefit of the pulsed "waveform" is that merely by varying the timing of pulses, the "frequency" can be adjusted to accomodate a wide variety of particle speeds and thus non-relativistic operation.

Takayama reported very promising theory and experiments demonstrating the barrier-bucket-style operation and acceleration for "super-bunches". In particular, this offers the possibility, finally, to do a loss-free transition crossing[2]. This would be a welcome addition to the arsenal of existing techniques used at transition energy, none of which have been completely successful. A hybrid RF/induction demonstration of focus-free transition crossing was made in 2005[2], and a full induction-only demonstration is in progress. In this context, one should note the presentation of Ng[12] in Session E; he points out that barrier bucket operation in storage rings with small slip factor are very susceptible to small phase or voltage errors whose cumulative results may be large.

Takayama mentioned also some potential difficulties. The barriers may be leaky if there is jitter in the pulse timing. The conventional beam control (radial and phase loops) used during acceleration in a synchrotron cannot be implemented. Only the timing but not the amplitude of the pulses may be varied, and so a pulse-inhibit style of beam control has been used[1]. A full induction-only demonstration of the *induction synchrotron* is in progress; pending complete results we classify the technique as "advanced".

Slip- and Barrier- Stacking

Seiya explained the procedures of radial (i.e. momentum) stacking[13] of convention RF-type and barrier-type buckets by frequency offsetting of injected batches, and their applications to increasing proton intensity/delivery in the Main Injector. In one mode, two Booster batches are accumulated for anti-proton production; and in another, multiple batches are stacked for delivery to NuMI.

Seiya reported successful operations[4] with two-batch slip stacking and experiments with multiple-batch stacks. These have proven a 60% increase in beam intensity and are considered a mature technology. However, there is a low energy beam loss attributed to cross-talk between buckets with inadequate frequency separation leading to mild emittance dilution. This hypothesis is confirmed in detailed simulations and tomographic reconstructions from experimental data.

Seiya reported also preliminary experiments of two-batch barrier-stacking and computer simulations of multi-batch barrier stacks. The early results are very promising. Studies will continue for a year, with the objective of confirming the operational procedure. We classify the barrier-stacking as "advanced".

CHALLENGES TO FFAGS

Scaling FFAGs

Scaling FFAGs[5] keep constant betatron tunes over a large momentum range. Three electron model machines were built in the 1960s, utilising betatron acceleration. There are two types of machine: the *radial sector* which

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uses reverse bends, and the *spiral sector* which employs alternating edge focusing. Several modern proton, or light ion, radial sector machines have been built or are under construction in Japan for medical[14] and ADS applications, and this may be considered a mature technology with expanding applications and developments. The spiral-sector type is more compact and lends itself to industrial and/or medical applications. Presently there are plans for a spiral machine as part of the KURRI-ADS[6]. The more complicated magnet shape (and beam dynamics) and limited space for RF-cavity makes their technical design more challenging; we class this spiral technology as "advanced".

Nonscaling FFAGs

Ruggiero presented the motivation for studying the non-scaling type FFAG: first proposed by Mills and Johnstone in 1997 for muon acceleration[15] and storage rings, they are now candidates for proton drivers and medical machines. The non-scaling type is more compact than either of the scaling types, and has the same high repetition rate advantage, but has strongly varying betatron tunes. The limited momentum range (typically 3:1) of present non-scaling FFAGs, which necessitates cascading of machines, is also seen as a disadvantage. The challenge for ultra-fast acceleration of muons is the dependence of revolution frequency on betatron amplitude which compromises the asynchronous acceleration. This is being addressed by a combination of measures: sextapole magnets and second harmonic cavities and is the subject of detailed simulations.

The challenges for the comparatively much slower acceleration of protons/ions are the tune variation, space-charge at injection, and lack of isochronism. Ruggiero reported on initiatives to address these issues from the Brookhaven perspective, including studies of machines with AGS-like and RIA-like specifications. In particular, the scheme of *harmonic-number jumping* as an alternative to RF sweeping: synchronism can be retained if the bunch slips an integer number of RF periods each turn. Originally proposed by Kolomentsky, this is independently rediscovered at BNL where there is intensive study. Pending the operation of a model/prototype non-scaling FFAG, this class of machine must continue to be considered "advanced".

Discussion period Baartman emphasized that the use of strong-focusing in cyclotrons (Thomas focusing, etc) predates that in either FFAGs or synchrotrons; moreover the cross-crest (or "gutter") acceleration in nonscaling FFAGs would be better named "cyclotron acceleration". Koscielniak expressed some scepticism as to whether the current slate of non-scaling designs would ever make real progress in reducing tune variation without impacting the dynamic aperture, or that the resonances could be crossed fast enough to avoid emittance growth in hadron machines. Nevertheless, it was clear that FFAGs have some niche applications: the scaling type to medical & ADS where the high repetition rate (kHz) is beneficial, the non-scaling type may be indispensible to ultra-fast acceleration of muons.

LASER TECHNOLOGY FOR HADRON SOURCES

It must be noted that two vastly different regimes of laser operation (pulse, power) were considered under this topic: microsecond, mega-watt; and sub-nanosecond, terra-peta watt. Yamane and Kondrashev reported on applications of the former, and Fuchs on exciting possibilities of the latter.

Laser ionization of H^0

Many long-pulse, high intensity proton rings rely upon H^- injection, and stripping to H^+ on a thin foil, as a way of circumventing the constraints on phase-space density implied by Liouville's theorem. However the foil is damaged (by heating) and the proton beam is degraded (develops halo and radio-activates ring) by multiple scattering of the re-circulating beam. Yamane described a foil-less scheme that relies on laser-assisted auto-ionization of H^0 in an undulator. The H^0 are prepared by Lorentz stripping of the extra electron in an upstream dipole. The undulator both broadens the Stark state and enhances conditions for auto-ionization of excited sates. The broad Stark state avoids having to scan the laser frequency. Yamane reported experiments[16] at Brookaven in 2004 on a simplified version of this scheme using a 200 MeV H^- linac beam. The initial results were disappointing; a number of possible contributing factors were identified, and will be remediated in future experiments to be reported at ICFA-HB2008.

V. Danilov gave a brief report of experiments, conducted at the Knoxville SNS with a more powerful laser source, on an alternative scheme based on laser-frequency scanning to strip H^0; initial results[17] look promising.

Ion Source by direct injection of laser-produced plasma

Kondrashev gave a convincing report that the *Direct Plasma Injection Scheme* (DPIS) type ion source could eliminate the need for multi-turn injection of light or heavy ions into a small synchrotron or FFAG accelerator. Though protons are not available from this source, there are future plans to investigate a target with a layer of hydrogen ice at 4K. Typical characteristics of the ions are 10s of mA current in a pulse length of 1-10 μs, and a repetition rate of 10-100 Hz; kinentic energy of beam is typically 10s of keV/charge. The plasma is ejected from a solid target illuminated by laser light and transported (in electrically neutral condition) from a high-voltage platform directly to the entrance of an RFQ where ions are extracted from the plasma and captured by the RFQ focusing channel. The result of several years development[18, 19, 20, 21], the DPIS demonstrates that a CO_2-laser-driven hadron source can be wedded to the front end of a conventional accelerator. A minor problem exits with deposition of vapourised target material on the focussing mirror, which must be protected.

Nevertheless, this is a mature technology available at modest cost.

Accelerator R&D for HEDP and WDM

Though strictly this was certainly not a talk on applications of lasers, it does serve to introduce the following report. Qin introduced the motivations for High Energy Density Physics (HEDP) and Warm Dense Matter (WDM): these are conditions encountered in the interior of stars and inertial confinement fusion, etc. Accelerator-driven HEDP experiments[7, 8, 23, 24] require typically sub-nannosecond, 1 microcoulomb pulses of mass 20 ions accelerated to several MeV to produce eV-level excitations, by Bragg-peak deposition, in thin foils. The critical issues are beam brightness and pulse compression. Qin described the Neutralized Drift (NTX) and Neutralized Drift Compession (NDCX) experiments, which have achieved transerse and longitudinal compression factors of 200 and 50, respectively, and their accelerator hardware. He described also the Pulse Line Accelerator (PLIA), a high-current transport experiment (HCX), and theoretical and computational efforts in support of all of these initiatives. Particularly novel devices are the ferroelectric volume plasma source and the PLIA which uses a helical-wound transmission line to slow the E-wave. It is clear that the HEDP/WDM application is pushing conventional accelerator technologies to their limits.

High-brightness proton & ion acceleration by pulsed lasers

Fuchs introduced members of the working session to the realm[25] of sub-picosecond, above-terawatt lasers and the hadron beams of dazzling brightness that they can produce. He carefully outlined the source/acceleration mechanism[26], which begins with electrons, the propagation of a polarization wave, and ejection of protons/ions from the back surface of a thin foil. The advertised beam-pulse properties are: extreme laminarity, normalized emittance $\varepsilon_\perp$ below 2π nano-metre-radian, pico-sec pulse length ($\varepsilon_\parallel \simeq 10^{-7}$ eV.s), energy 10s of MeV, $10^{11} - 10^{13}$ ions per pulse. Fuchs then outlined methods to characterize the beam properties, transport and focusing mechanisms, and collimation and energy selection[27]. Neutralized, ballistic transport allows to overcome the intense space-charge forces.

In the discussion period, it was obvious that this T3-laser type of ion source could find immediate application to HEDP and WDM where it offers time-structure far superior to conventional methods, and delivers the requisite number of ions per pulse. However, a problem with the proton/ion beam from this source is the need for better energy selection - an active and promising area of research[27]. Simulations of target heating show non-uniformities of WDM second-foil target temperature greater than 10-20% because of the variable energy spectrum. It was discussed whether a better application of the laser would be to shine it directly on the WDM target foil; it was concluded that it is difficult to obtain homogeneous heating with a laser alone, and that an ion beam is a better intermediary of energy density because the various parameters (energy, current, deposition depth, etc) allow greater flexibility for measuring “equation of state” effects.

Further discussion centred on whether this type of ion source could find use in proton-drivers or medical accelerators, and what are the limitations on time-structure. One must trade-off repetition rate against kinetic energy: 1 MeV at 1 kHz, 10 MeV at 1-10 Hz, 100 Mev at 10^{-3} Hz are available now. However, laser technology continues to advance rapidly and Fuchs predicted that substantially higher repetition rate would be available in 2-3 years; indeed the present performance was not dreamed of three years ago. The lower repetition rate, say 1 MeV at 1 kHz, is less of issue for medical[28] applications where conformal scanning in partitions is considered essential for accurate dose control. In any event, this ultra-bright, ultra-intense, short-pulse hadron beam is one that the accelerator community should think creatively how to utilize.

SUPERCONDUCTING TECHNOLOGY

Fast pulsed SC magnets

Muehle introduced the 5-ring Facility for Antiproton and Ion Research (FAIR) at GSI as the motivation. In particular the SIS100 and SIS300 synchrotrons whose specifications dictate two different species of dipole magnet: the super-ferric type, low field (2T), fast ramp (4 T/s); and $\cos\theta$ type: high field: (4-6T), slow ramp (2 T/s). The FAIR prototypes builds on mature UNK and RHIC technology, respectively. However, the FAIR requirements are more demanding: faster ramping may lead to higher heat load and multipole content due to eddy and persistent currents, etc; and this must be avoided. The greater number of magnet cycles necessitates greater mechanical integrity. Muehle detailed several technical improvements to each magnet type which lower the AC losses to an acceptable level; among these is a filament and cable R&D program and measures to facilitate heat removal. The ramp-rate of the BNL $\cos\theta$ magnet has been increased more than 10-fold.

The field of the super-ferric, window-frame magnet is iron-dominated and the field errors are well under control. There are extensive measurements of the multipole content of the $\cos\theta$ magnet in DC and AC conditions; for the most part results are in agreement with Roxie and Opera simulations, a slight discrepancy in the 10-pole is under investigation. Possible directions for future R&D include a 2-layer-coil $\cos\theta$ magnet based on UNK design; and doubled length, curved $\cos\theta$ magnet at lower field extrapolated from the BNL-prototype. The cable R&D will continue.

To summarise, results from SIS100 and SIS300 prototype magnets[22, 9] are very promising and this technology is nearly ready for industrialization. This is a product looking for a wider market; some interest from superLHC. Discussion questioned whether rapid cycling (e.g. 10 Hz)

Table 1: List of Some Advanced Accelerator Technology Hardware R& D at Labs

Technology	Institution
FFAG scaling	KEK; Osaka U. (PRISM); Kyoto U.; Grenoble, Kyushu U. (ADS)
FFAG non-scaling	UK (EMMA), Tech-X in US Electron Energy Corp.; RADIAbeam (LA)
Induction acceleration	KEK
Slip stacking	FNAL
Barrier rf	FNAL, JPARC
High-intensity short-pulse laser for hadron acceleration	CNRS/LULI; Osaka U.; Livermore; LANL; RAL; Max Planck Inst; Max Born Inst. U. of Nevada; General Atomic; Rochester U.; GSI; CEA/Bordeaux, CEA/Saclay; JAEA; IENA U., Germany; Imperial College, London; Belfast U.; Michigan U.; etc.
Direct plasma injection	ITEP, Russia; RIKEN, BNL
HEDP, WDM SC pulsed magnet	VNL (PPPL, LBL,LLNL) GSI, ITEP, Russia;IPN, Orsay GSI; IHEP, JINR (Russia); BNL; CERN; INFN; CEA-Saclay
SC spoke cavity	ANL; LANL; IPN-Orsay; FNAL; Julich
Laser stripping	KEK-BNL; SNS
Advanced cusp ion source	VECC, India; RIKEN, etc

would be available in the foreseeable future. It was concluded that there are other ring-limitations, such as eddy current heating of vacuum chambers, which become an earlier impediment; the wide magnet apertures for a ceramic pipe would be prohibitively expensive.

Spoke cavities

Kelly made a strong case for the adoption of spoke-type cavities as the technology of choice for 350 MHz superconducting (s.c.) linacs accelerating hadrons in the range $0.1 < \beta \leq 0.6$ where kinematic $\beta = v/c$. In the range $0.6 < \beta < 1$, the multi-cell elliptical type resonators are preferable. Development of s.c. spoke-type cavities began in the 1990s and has flourished at several laboratories: ANL, LANL, Julich, IPN Orsay, etc. Particular emphasis was given to the 3-spoke cavity[10] developed at ANL; a detailed comparison at $\beta = 0.6$, with the SNS 6-cell elliptical cavity shows the heat-load and effective gradient to be similar. The single- and multi- spoke-type resonators have some intrinsic advantages (larger longitudinal acceptance due to lower frequency, greater mechanical stiffness and resilience against microphonics, higher R/Q, etc) and come into their own for $\beta < 0.6$. Kelly mentioned several potential applications for the spoke cavity: AAA, XADS, EURISOL, FNAL proton driver linac[11]. The large range of β that can be accepted, and the longitudinal acceptance, make them particularly amenable to transport (simuntaneously) multiple charge sates, as is envisioned for RIA. This technology is ready for industrialization.

Final Discussion The final discussion centred on composing a table (see above) of the technologies considered in this session, and listing the laboratories participating in hardware R&D.

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