FIFTY YEARS OF SYNCHROTRONS

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Abstract

The idea of a pulsed magnet ring, fundamental to the synchrotron, appeared in a proposal by Oliphant [1] in 1943 and was followed by the independent discovery of phase stability by Veksler [2] in 1944 and McMillan [3] in 1945. This opened the door to a demonstration of synchrotron acceleration to 8 MeV by Goward and Barnes [4] in a converted betatron at Woolwich Arsenal, UK. The event, which took place in August 1946, was followed only two months later by the operation of the General Electric Laboratory's 70 MeV machine at Schenectady, USA built by Elder, Gurewitsch, Langmuir and Pollock [5]. The fifty years that follow have seen projects spanning almost six orders of magnitude in energy. The phenomenal success of the synchrotron principle was sustained by two other important discoveries, that of alternating-gradient focusing and the use of colliding beams. This paper records the major landmarks in the early history of the synchrotron.

1 INTRODUCTION

Never, with the possible exception of developments in aerospace, have physicists, engineers and managers of men and of politics tapped as rich a vein of progress as the synchrotron. Propelled by three major innovations in theory — phase stability, alternating gradients and collider rings — a series of projects stride through five decades, each generation surpassing its predecessors by an order of magnitude.

The synchrotron principle, originally conceived to extend the range of an electron accelerator — the betatron — soon took over the cyclotron's role as an accelerator of ions and protons to high energy. Successive synchrotron projects were driven from the outset by the needs of particle physics, first to surpass the nuclear potential barriers probed by cyclotrons in the thirties, and then, with increasing energy, to produce a sequence of massive particles which proved the key to understanding matter on an increasingly infinitesimal scale. Recent years have also seen a diversification of powerful lower energy machines for the production of synchrotron radiation and for therapy. The world's two largest synchrotrons are now LEP for electrons and the LHC project for protons.

2 THE SYNCHROTRON PRINCIPLE

At the beginning of the second world war, the skills of cyclotron builders in the US were diverted to the task of electromagnetic separation of uranium. In this they were joined by colleagues from the UK. Ideas are often born from a combination of stimulating company together with an ample time to reflect and so it happened that Sir Marcus Oliphant, found himself in 1943 at Oakridge supervising the business of transforming a laboratory experiment into a large scale industrial process for isotope separation. As E.O. Lawrence's deputy he was given the owl watch and "with little to do unless troubles developed" occupied his time by speculating on plans for his return to Birmingham when war was over. He wrote a memo [1] to the Directorate of Atomic Energy, UK in which he proposed a new method of acceleration:

> *"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field ... which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes."*

His idea was not greeted with enthusiasm at a time when more important business was afoot but he nevertheless persevered, encouraged by Lawrence, as he left for England.

3 PHASE STABILITY

A little later, in 1944 Vladimir Veksler [2], in a paper to the USSR Academy of Sciences, showed that the orbital period in a cyclotron may be maintained if field and frequency are adjusted to take into account the increased relativistic mass and went on to explain the mechanism which later came to be dubbed phase stability.

Before this paper had time to reach the US, Ed McMillan had written a letter to the editor of Phys. Rev. [3] in which he coins the terms "phase stability" and "synchrotron", defined as a machine in which both frequency and magnetic field vary.

In 1963 McMillan and Veksler were jointly awarded the Atoms for Peace Prize. The citation read:

> *From their insights have come.. the synchrotrons, which have introduced us to the finer structure of the nucleus...*

Oliphant recalls that, after his return to Birmingham he was "shattered by the publication of the comprehensive and beautiful papers by McMillan and Veksler" which, he admits did prove powerful support for his proposal to the DSIR for the construction of a 1000 GeV synchrotron. One presumes that he was disappointed to find no reference to his pulsed ring-magnet idea.

He writes retrospectively [6], and modestly, that "If I had been capable of a complete analysis, which is doubtful, it is improbable that I would have realised the synchro-cyclotron principle as did Veksler and McMillan" but that he knew at the time "..what would happen to particles which either led or lagged in phase with respect to voltage across an accelerating gap."

Stan Livingston and John Blewett [7] writing with the memory of these events barely faded, calm these contested waters and attribute the first proton synchrotron proposal to Oliphant (1943) while praising McMillan's paper on phase stable acceleration as a classic.

4 PROOF OF THE SYNCHROTRON PRINCIPLE

Oliphant was at this time still busy lobbying the UK funding agencies for money for his proton synchrotron when he heard McMillan had been given the green light to construct an electron machine for 300 MeV at the University of California. However other enthusiasts were in the field eager to be the first to prove the principle.

Late in the war Donald Kerst in the US had built a "portable" betatron at the request of the Woolwich Arsenal Research Laboratory in the UK. Frank Goward was at Woolwich when he read McMillan's paper and perhaps the mention of the 'betatron condition' in that paper triggered him to realise that by mounting a quarter wave open-weave liner in the betatron and applying r.f. to it, synchrotron acceleration might take over when betatron acceleration faded out at the point that the yoke began to saturate. Fifty years earlier than the time-of-writing Goward and D. E. Barnes [8] were able to use this machine to demonstrate synchrotron acceleration of electrons from 4 to 8 MeV. The influence of Lord Rutherford's 'string and sealing wax' spirit of improvisation on a generation of UK physicists is perhaps to be seen in Figure 1.

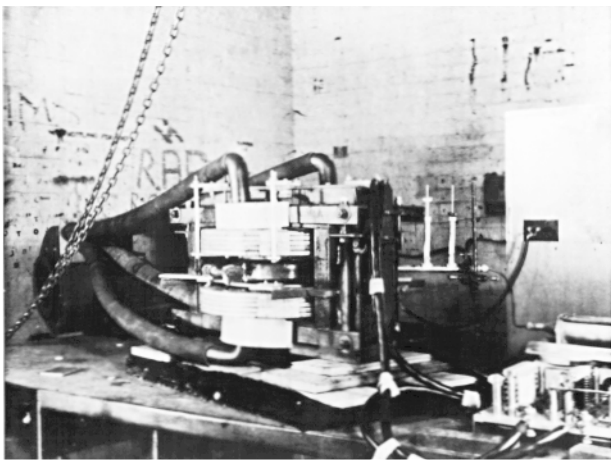

Figure 1 The 4 MeV betatron converted to an 8 MeV synchrotron

In Figure 2 we see a combined oscilloscopic trace recording the sum of magnet field, injection pulse, r.f. envelope, and a beam loss monitor. The upper trace, with r.f. switched on, to turn the betatron into a synchrotron, shows a barely discernible blip (c) at 80° in the waveform indicating some beam had been accelerated to 8 MeV instead of the usual 30° point of 4 MeV.

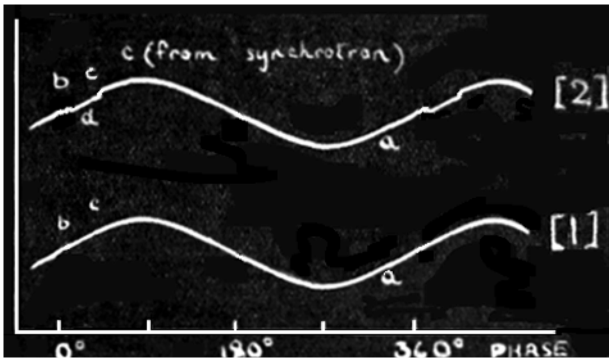

Figure 2 Oscilloscope traces showing normal betatron acceleration, below, and above as a synchrotron

On the other side of the Atlantic, a team at the General Electric Co. at Schenectady who had had considerable experience in building betatrons were also in pursuit, egged on by the young John Blewett to build a 70 MeV version of McMillan's machine and to get there first. They just failed to beat the Woolwich people to the post by a month or two. However they had the consolation that this machine, with a glass vacuum chamber was the first to produce synchrotron radiation in visible form [9, 10].

5 PROTON SYNCHROTRONS

The first synchrotrons were electron machines but projects for proton synchrotrons aiming at energies above 1 GeV were not far behind. Oliphant was back at the University of Birmingham in the shadow of the replica of the Siena campanile which adorns that campus. He had made his bid early to construct a 1 GeV proton machine but he was becoming bogged down in the red tape and lack of imagination which abounded in post war Britain. Europe was then unused to big-science and much of his work force had to come from the graduate students in his department.

There were technical problems to be solved too. Tuning the r.f. system to the huge swing in frequency had never been tackled before and its solution involved plunging an uninsulated and highly non-linear inductor, Figure 3, in a mercury bath. The finer, low level, adjustment was managed by filing the shape of a rotating disc.

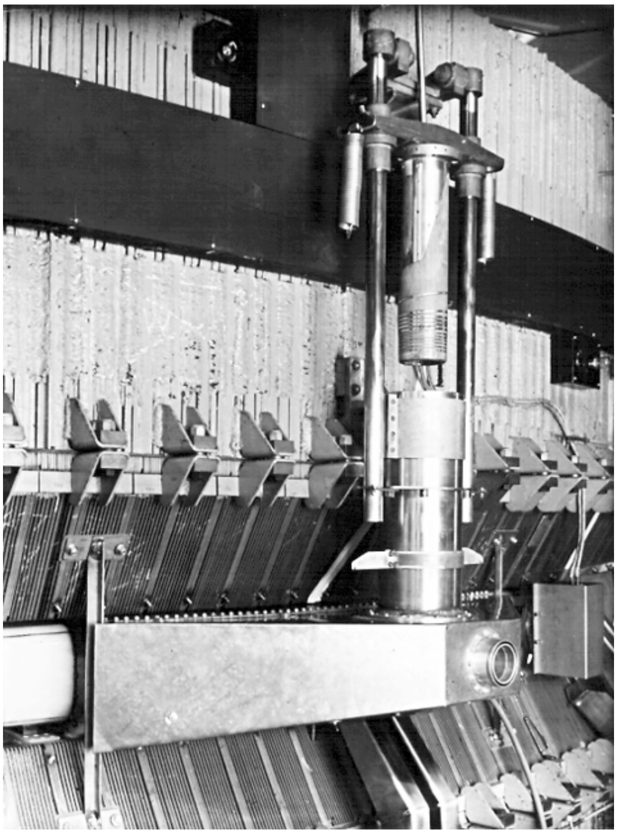

Figure 3 Oliphant's non-linear inductor withdrawn from its mercury bath

The pulsed waveform for the magnet excitation was produced via a motor generator set servo controlled by light reflected from 120 mirrors on the disc's periphery. The machine reached just short of 1 GeV for the first time in July 1953 overtaken by one year by the 3 GeV Cosmotron at Brookhaven but before the 6 GeV Bevatron started up in 1954. The Bevatron had also had its trouble. The aperture required for a weak focusing machine was difficult to estimate and a fall-back solution of low energy had a huge aperture 4.3 x 1.2 m, which gave rise to rumours that it was destined to be the world's most powerful accelerator of Jeeps [11] (provided, we are told, their windshield was down). Its builders had been distracted for a year or two in mid project to construct a large accelerator as part of a defence project.

Meanwhile the Cosmotron team which included Stan Livingston, John and Hildred Blewett, Ernest Courant, Ken Green and N. Blackburn had refined their aperture to a mere 1.2 by 0.22 m and were ahead of the field. When they first switched on in early 1952 they began to doubt the optimism of their calculations, but after two worrying months found that they had been fooled by a burnt out voltage divider in the r..f. system. Once this was fixed they made what the *New York Times* in May 1952 headlined their first "Billion Volt Shot".

6 STRONG FOCUSING

The Cosmotron, a typical weak focusing synchrotron had a "C" shaped magnet open to the outside. To ensure focusing in both planes, the field gradient should be negative but not too strong. The upper energy of the Cosmotron was limited by the extra negative gradient caused by saturation. Livingston had the idea of compensating this by reinstalling some of the C magnets with their returns towards the outside but he was worried in case the focusing at low energy would be affected.

Courant was given the task of checking the effect of this alternating gradient and reported that — far from being harmful — the focusing seemed to improve as the strength of the alternating component of the gradient increased. Snyder, as befits a good theorist who should always be ready with an *a postiori* explanation, reminded them of the optical analogy of alternating focusing by equal convex and concave lenses and the AG focusing idea was born

A paper was published near the end of 1952 by Courant, Livingston and Snyder [12] but then it was found that the idea had actually been patented earlier by Nick Christofilos [13].

As if on cue the CERN visitors — Odd Dahl, Frank Goward and Rolf Wideröe — arrived and, hearing of the new idea, immediately abandoned plans for a 10 GeV weak focusing machine in favour of a 25 GeV PS for the same price. Brookhaven had already planned such a machine as their next step, the AGS.

7 AGS AND PS

Although, in a sense rivals, the AGS and CERN teams shared their expertise throughout the constructions of their machines. As a first step John and Hildred Blewett, joined Dahl and Kjell Johnsen in Bergen building the first prototype high gradient synchrotron magnet before moving to Geneva in the fall of 1953. John Blewett reports that it was a youthful Johnsen who showed there was little to fear from the phenomenon of transition which was one of the headaches stemming from the alternating focusing system.

Another headache was that, in their enthusiasm for the new alternating gradient principle, designers proposed large numbers of periods and high Q values. John Lawson pointed out that these machines were particularly susceptible to transverse non-linear resonances which became much worse at large Q values. Even at more modest Q values, AG machines were thought to be very sensitive to errors of all kinds. John Adams and Mervyn Hine at CERN made it their business to ensure that the necessary precision of alignment and magnet performance was respected and CERN recruited a team of some of the most painstaking engineers in Europe to build the PS. This team became a legendary asset to CERN as it tackled a series of "difficult" synchrotrons — ISR, SPS, SPPbarS, LEP and the present project — LHC. Adams was so impressed by the challenge with which the PS confronted its designers that he advised his own national laboratory to keep to the weak focusing principle for the construction of NIMROD pointing out that the PS was only designed for 10^{10} ppp.

Indeed the weak focusing synchrotron remained the preferred choice of the cautious and the Cosmotron was followed by the ZGS at Argonne, the Synchrophasatron in Dubna, Saturne in France and Nimrod in the UK.

Nimrod had a large motor generator-alternator whose load rose from zero to 100,000 horse power in 0.75 seconds storing energy in a huge flywheel which was driven from the mains, which delivered the energy to pulse the magnet. One night a pole on the rotor broke and it was only the heroism of an operator racing over a catwalk towards the circuit breaker above the monster writhing in its death throes that prevented the export of a large rotating flywheel across the Channel to France.

By 1959 CERN's PS was ready for testing, ahead of Brookhaven's AGS and did indeed falter at transition until Wolfgang Schnell produced a circuit he had built in a Nescafe tin to change the phase at the moment of transition. Schnell, his box and a few BNC connectors brought the beam through transition to full energy

8 SYNCHROTRONS IN RUSSIA

The history of the synchrotron in the Soviet Union followed parallel lines to that in the West. Their first application of Veksler's phase stability principle was in the direction of the synchrocyclotron or "Phasotron" as Dubna called it. The first operation of this machine was timed to be on Stalin's 70th birthday which we are told is a Soviet tradition. This was followed by two proton synchrotrons whose energy and switch-on date were nicely judged to bridge the gap left in the West. Dubna's 10 GeV weak focusing “Synchro-phasotron” surpassed the 6 GeV Bevatron and, from 1957 until the 25 GeV PS at CERN was finished, offered the highest energy in the world. The same was true of Serphukov's "U-70" which used alternating gradient focusing and held the world record from 1967 until 1972 when Fermilab started up.

9 FERMILAB

The controversial mastermind behind this second generation proton synchrotron was Bob Wilson who had worked with Lawrence in the cyclotron era and had built a number of successful electron synchrotrons at Cornell. He had had no hesitation in adopting the AG principle for these machines and he was to add his own particular flavour to the construction of the new FNAL machine, a flavour which he had inherited from his mentor Lawrence and which was also to influence W. Paul in Bonn and Gus Voss in DESY as they built their electron machines. By separating the functions of the combined focusing and bending magnets of the AGS, and PS and using pure quadrupole and dipole units, he found he could squeeze more bending power per meter in the lattice. With this and other bold economies such as reducing as many of the gauges, taps and switches that threatened to adorn each of the ring’s 1000 magnets, not to mention applying the production line techniques of Henry Ford to the construction, he was able to double the target energy to 400 GeV and propose its completion in a mere 5 years. The first bold innovators in such ventures are perilously exposed but he kept his promise to complete the machine in only 5 years and thereby gain a march on the rival SPS at CERN stuck in a political quagmire, starting construction only as Wilson’s machine began to run. Later the addition of a superconducting ring, the Tevatron, was to complete the world’s first superconducting hadron collider at Fermilab.

10 ISR

Following the PS, CERN constructed the first large hadron collider modelled upon the pioneering electron machine ADA and the brilliant series of innovative electron storage rings built at the Budker Institute. The challenge of colliding two 40 amp DC proton beams in the 30 GeV intersecting proton beams was formidable and achieved only after almost all the colliding effects which affect synchrotrons had been identified and cured thanks to the team led by the same Johnsen who had reassured the accelerator fraternity in 1953 that transition was “no problem”.

11 SPS

Following the ISR, the 400 GeV SPS at CERN proved a worthy if tardy rival to FNAL. Adams who had chosen to imitate much that was good in FNAL had taken his usual painstaking care with the reliability and tolerances of the machine. This more than proved its worth when Rubbia and van der Meer proposed to use it as a huge collider for protons and antiprotons — a facility which led to CERN’s first Nobel Prize.

12 DESY

In parallel with Nimrod, FNAL, ISR and SPS, DESY constructed an impressive series of synchrotrons and storage rings. Naturally their energy was limited by synchrotron radiation but starting with the 4 GeV DESY synchrotron followed an electron storage ring DORIS, a larger one called PETRA of 30 GeV, the predecessor of LEP, and in recent years the first European superconducting machine HERA in which 800 GeV protons collide with polarised 30 GeV electrons.

13 ACKNOWLEDGEMENT

Fifty years is longer than most people’s professional lives. Fortunately, there are still those alive and well who remember the first fifteen. And it should be said that it is these years that are the the least well documented and yet

the most interesting. To these invaluable sources of information the author is most grateful and, if this record differs in some way from their memory of events, they are asked to make allowances for the fact that the recollections even of wise men are sometimes at fault, and less wise historians are notorious for filling in their ignorance with imaginative but often inaccurate stories. We have clearly already reached the plateau of the historians learning curve.

A number of sources, J. P. Blewett, D. Edwards, L. Hobbis, D. Judd, K. Johnsen, J. D. Lawson, E. Lofgren, I. Meshkov, W. Schnell, V. Suller, R. R. Wilson, and many others who have given advice are to be warmly thanked and readers whose favourite machines are not mentioned (Italy and Japan spring to mind, both of whome have had major programmes of synchrotron construction) are kindly asked to accept the excuse that time and the number of pages allotted are limited.

REFERENCES

[1] M.O. Oliphant, *The acceleration of particles to very high energies*, Classified memo submitted to DSIR, United Kingdom, Sept. 1943, now in University of Birmingham Archive.

[2] V. I. Veksler, *A new method of accelerating relativistic particles*, Comptes Rendus (Dokaldy) de l'Academie Sciences de l'URSS, **43**, 8 (1944), p. 329-331.

[3] E. M. McMillan, *The synchrotron – a proposed high energy accelerator*, Phys. Rev. **68**, 143 (1945).

[4] F. K. Goward and D. E. Barnes, Nature, **158** (1946), p. 413.

[5] F. R. Elder, A. M. Gurewitsch, R. V. Langmuir and H.C. Pollock, *A 70 MeV synchrotron*, Journal of Applied Phys **18**, 9 (1947), p. 810-818.

[6] M. Oliphant, *The Genesis of the Nuffield Cyclotron and the Proton Synchrotron*, Univ. Birmingham Dept. Phys. (1967).

[7] M. S. Livingston and J. P. Blewett, *Particle Accelerators*, McGraw-Hill, New York, 1962.

[8] F. K. Goward and D. E. Barnes, Nature, **158** (1946), p. 413.

[9] F. R. Elder, A. M. Gurewitsch, R. V. Langmuir and H. C. Pollock, Phys. Rev. **71** (1947) 829.

[10] F. R. Elder, R. V. Langmuir and H. C. Pollock, Phys. Rev. **74** (1947) 52.

[11] D. Judd, private communication.

[12] E. D. Courant, M. S. Livingston and H. S. Snyder, *The Strong-Focusing Synchrotron – a New High-Energy Accelerator*, Phys. Rev., 88 (Dec. 1952), 1190-6 and E. D. Courant and H. S. Snyder, *Theory of the Alternating-Gradient Synchrotron*, Annals of Physics, No. 3 (1958), 1-48.

[13] N. C. Christofilos, Unpublished report (1950) and U.S. Patent no. 2.736,799, filed March 10 1950, issued Feb. 28th, 1956.