# Historical Notes on the Theoretical Description of Intrabeam Scattering

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It is a great pleasure and privilege for me to be here to share these historical notes on intrabeam scattering. They are taken from the presentation that I gave on behalf of Anton Piwinski, James Bjorken and myself at the January 28, 2017, meeting of the American Physical Society where we received the Robert R. Wilson Prize for our work on the intrabeam scattering.

First, I would like to take the opportunity to talk about Anton's reflections on the beginning of the investigations of intrabeam scattering. He first heard about this phenomenon in 1973 while attending a workshop in Italy. He recalls learning that intrabeam scattering could be a serious problem in proton accelerators. Since DESY in Hamburg was discussing at that time a new proton storage ring, he decided to investigate this problem.

In the literature, he found several reports on the Touschek effect, but little about intrabeam scattering. The Touschek effect and intrabeam scattering are two different aspects of the same phenomenon, namely Coulomb scattering within a charged particle beam. For the Touschek effect, only large scattering angles are taken into account. On the other hand, for intrabeam scattering, small scattering angles are considered and it is assumed that all changes of coordinates due to the scattering are small compared to the beam dimensions. For the Touschek effect, sufficient theoretical investigations existed that allowed for a reasonable calculation of the beam lifetime due to the effect. However for intrabeam scattering, there were only a few attempts to estimate the transfer of oscillation energy from one direction to another, mainly from transverse to longitudinal, i.e. from betatron oscillations to synchrotron oscillations, but not vice versa, which is necessary for a realistic description. Indeed, intrabeam scattering is a mutual exchange of oscillation energies among all three directions and only by taking into account all energy transfers can one obtain a complete description.

Fig. 1 shows a typical example of a measurement of this effect that was performed in 1984 at CERN's Super Proton Synchrotron (SPS) at an energy of 300 GeV. It depicts the longitudinal distribution of a proton bunch on the left side and an antiproton bunch on the right side at different times. The time difference between successive curves is a quarter of an hour. The main difference between the two sets of curves is the particle density, or number of particles in a bunch, with the density of the proton bunch being an order of magnitude larger than that of the antiproton bunch. Consequently, the growth of the proton bunch length is clearly stronger than that of the antiproton bunch. Similar measurements also were made for the bunch width and for the bunch height. All such measurements in various storage rings show such a slow change of the beam dimensions.

Appendix 1 gives a brief review of early investigations on intrabeam scattering. Bruck and Le Duff in 1964 and Pellegrini in 1966 performed the first investigations, where they calculated the transfer of oscillation energy from one direction to another. In 1974, Piwinski published his classic paper in which he included, for the first time, energy exchanges among all three direction, including energy losses due to transfers from one direction to the other.[1] Thus at last, Piwinski's work allowed one to calculate the development of the beam dimensions over a long time.

In 1977, Simon van der Meer was working on his new idea about the stochastic cooling of beams, for which he would later receive the Nobel Prize. He asked for the most precise calculation of the rise times due to intrabeam scattering, because stochastic cooling would have to compete with intrabeam scattering. Then Sacherer and Piwinski independently derived formulae, including the derivatives of the lattice functions. Huebner, Möhl and Sacherer incorporated this work into a computer program, which researchers used at a number of accelerator facilities. Then in 1983, Bj and I used quantum field theory to develop a completely new description of intrabeam scattering that included the full set of lattice parameters and their derivatives.[2]

Most of you present today, as well as many others, are completely unaware that Bj ever had anything to do with the theory of particle accelerators. But for a long time, he has been extremely proud to have earned a membership card in the union of accelerator theorists. However, he related me that he never dreamed that it would come to this.

Bj's interest in the subject began in the 1970's at SLAC, thanks in large part to his close association and friendship with Burton Richter. Burt put into his hands the classic Matt Sands tutorial on electron storage rings.[3] When he moved to Fermilab in 1979, he vowed to learn about proton machines as well. By 1981, he recalls that

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[1] A. Piwinski, Proc. 9th Int. Conf. on High Energy Accelerators, p. 405 (1974).
[2] J. Bjorken and S. Mtingwa, Particle Accelerators, Vol. 13, p. 115 (1983).
[3] M. Sands, SLAC Report 121 (1970).

he had progressed enough that he became something of a groupie within the community of Fermilab accelerator theorists. Then, in the summer of 1981, Alvin Tollestrup introduced him to the intrabeam scattering problem, which he had been working on himself. As mentioned earlier, there had been a lot of prior work, the most important being by Anton. But the most general case of a strong-focusing machine lattice was not yet fully understood. And at Fermilab, this case needed to be understood in the context of the design of the Antiproton Accumulator, in which stochastic beam cooling was being implemented, and of the Tevatron.

Bj informed me that his recollection of the details, not to mention his comprehension of the subject matter, has greatly deteriorated in the more than three decades since that time. But since he is a packrat, he found a fat file full of notes from that period. From them, it appears that he rather quickly got up to speed on the problem. He related to me that, in retrospect, the reason for this lay in his experiences in the world of particle-physics theory. A bunch of 10 billion protons traveling down a beampipe at nearly the speed of light is not totally dissimilar from an ion containing a hundred nucleons doing the same thing, or even a single relativistic nucleon containing all those quarks and gluons, also doing the same thing. So, now in hindsight, it appears to Bj that from the start, he was in something of a comfort zone, and could apply the manifestly-relativistically-invariant formalisms developed for particle theory, especially by Feynman, to this problem.

Evidence for this exists in his own handwritten notes, dated August 1981, which are in particle physics language, and which exhibit for sure a fresh approach to the problem. Evidently, the first problem facing him was whether he could reproduce what Piwinski had already done. On page 8 of his first note appears the sentence "Translate into ordinary lingo." By page 9, he had moved into the accelerator physics language: there is a line “We follow Piwinski in defining the following variable…” And by page 11, the conclusion was “This agrees with Piwinski’s formula, although it may still be accidental.” Two days after this first note, Bj created a second one, which rephrased and streamlined the computations present in the first one. The key mathematical tactic was a famous identity used by Feynman and Schwinger to evaluate integrals associated with Feynman diagrams. It is not clear to Bj whether there was a genuine “aha” moment in that two day interim. And this is about the time in late August 1981 that I, who had just completed a postdoctoral position in the Fermilab theoretical physics group, and was transitioning to a new position, went to Bj looking for a problem. Bj recalls that intrabeam scattering was all that he could offer. But despite having to start from scratch in learning the trade, I signed on. So it is possible that the reason Bj wrote those two notes was to provide me with something better than the chaotic scribbling, barely intelligible to Bj himself, that he used when working alone.

Between the fall of 1981 and the spring of 1982, I was rapidly riding up the learning curve, and more and more of the problem landed in my hands. I also would like to credit the excellent Matt Sands tutorial on electron storage rings for providing me with my first introduction to the basic theory of particle accelerators. There was all through this period a close working relationship with Alessandro Ruggiero, the resident Fermilab accelerator theorist most deeply involved in the intrabeam scattering problem. He produced several internal notes during this period, and is acknowledged in our paper as well. And in Bj’s file is a short message from Piwinski, indicating that he was during this period also up to speed. We found ourselves in agreement on the results, although there was a pesky overall factor of two that had to be negotiated amongst us.

In a nutshell, the physics idea expressed in our paper is that, viewed in the rest frame of the bunch, intrabeam scattering tends to make the bunch grow in size, and to evolve toward isotropy in momentum space. On the other hand, accelerator designers impose strong, time-dependent electromagnetic fields that squeeze and stretch the bunch in ways designed to inhibit such behavior. The formulae that we derived exhibit this physics somewhat more transparently than what had been done before. Finally, by the summer of 1982, Bj and I had created a draft of our paper, which we subsequently published in the journal, ***Particle Accelerators***.[4]

It was about this time that I actually made a foray into experimental work. Fred Mills, who was in charge of magnet design and construction at the Antiproton Source, asked me to help him to develop an analytic approach for designing the endpacks to be installed on either end of each magnet so that the integrated field through each magnet would meet the design specifications. We succeeded in this important task. Each prototype magnet that was fabricated would have its integrated field measured and we would calculate how to design the endpack. Fortunately, we were spot on for each magnet, greatly reducing the time required to produce the Antiproton Source dipoles and quadrupoles.

With two accelerator victories under my belt, I formally joined the Antiproton Source Stochastic Beam Cooling Group in 1983. Since Bj and I had just published our paper on intrabeam scattering, stochastic cooling was a natural fit for me to further my interest in accelerator physics. There I worked closely with John Marriner in finalizing the vacuum and beam sensitivity designs of the pickup and kicker electrodes. Glen Lambertson and his colleagues performed much of the early work at Lawrence Berkeley National Laboratory (LBNL), where they designed and constructed the prototype devices. I was detailed to Fermilab's

[4] Ibid.

technical staff that fabricated the pickups and kickers, where I performed quality assurance tests to ensure their microwave performance, collaborated with James Simpson and colleagues at Argonne National Laboratory's 20 MeV electron linac in performing beam tests on LBNL prototype electrodes, and oversaw the installation of the pickups and kickers into the Debuncher and Accumulator Accelerators in the Antiproton Source tunnel. As shown in Fig. 2, I even had the good fortune to be featured in the August 1985 issue of **Ebony Magazine**. The caption states that I was standing next to a superconducting magnet. In fact, it was one of our stochastic cooling tanks, but I think the public has forgiven the editors.

As depicted in Fig. 3, the Antiproton Source consisted of a target station, beam transport lines, and two small accelerators called the Debuncher and Accumulator, which were both contained in the same tunnel. Protons were extracted from the Main Ring at 120 GeV and impinged upon a tungsten-rhenium target, whereby a Li lens would focus secondary particles off the target, and a pulsed dipole magnet would steer 8.9 GeV antiprotons toward the Debuncher. This accelerator converted the antiproton bunches into a continuous beam and began the process of cooling it, namely reducing its momentum spread and transverse phase space. The final cooling and accumulation of the antiprotons into a high-density core in momentum space occurred in the Accumulator. In our work, Bj and I wanted to ensure that intrabeam scattering in the Accumulator would not prevent the goal of stacking $4\text{x}10^{11}$ antiprotons in the core every 4 hours. Our theoretical analyses and numerical simulations showed that intrabeam scattering would not be a problem, so we were all relieved.

Since I have gotten my hands both full of chalk dust as a theorist and grime as an experimentalist, I would like to pause for a moment to reflect on a method for determining for which career one is better suited. First of all, I think that we can all agree that a particle accelerator is one of the most complex scientific devices to design, construct and operate. There are many systems that must work in tandem and to high precision. At the Tevatron complex, I was involved in the construction of the two systems already mentioned: magnet and stochastic cooling. Relative to the latter, there were 23 large tanks like the one shown in Fig. 2, 12 in the Debuncher and 11 in the Accumulator, each containing numerous delicate, even brittle, pickup and kicker electrodes. John Marriner and I were responsible for ensuring that those intricate devices worked once commissioning commenced. While we were constructing and installing them, I cannot tell you how many powers-of-ten times I prayed that they would indeed work. On the other hand, John was so sure that all was well, even when some major glitches had to be resolved. So, all the time, I was busy praying and he was busy smiling. From that experience, I surmised that if you spend more time praying than smiling, then you are really a theorist and should probably stick to your pen and pad. As for the entire Antiproton Source, when all systems were turned on during the commissioning and things started working, I'm sure John felt that it was indeed a job well done, while I felt that it was truly one of the greatest miracles in human history. Indeed the Antiproton Source worked well over the following decade, being a crucial element in the 1995 discovery of the top quark. Somehow I feel that I and all my accelerator colleagues at the Antiproton Source and Tevatron should be counted as co-discoverers of the top quark, given the extreme sweat and tears that it took to put those accelerator systems into place for the detectors. I think that our high energy community should take a serious look at devising a system to reward those on the accelerator end with co-authorship of papers involving major discoveries.

Since those early years of the Antiproton Source, many improvements and upgrades were made, including to the stochastic cooling systems. Around the year 2000, a decade after Bj and I had left, intrabeam scattering finally caught up with Fermilab. The magazine, ***Science***, featured a story on the lab's problems.[5] I quote:

> "A year and a half ago, the Tevatron, which smashes protons and antiprotons together at enormous energies, began operating again after a $260 million refit. Despite months of tinkering, however, scientists and engineers couldn't boost the beam's luminosity – its "brightness" – high enough to begin the bulk of the accelerator's research program…..
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> A major problem with the accelerator lies in the system that accumulates, accelerates, and stores antiprotons – which, unlike protons, are hard to produce. Fully 80% of the antiprotons were supposed to survive the trip from the accumulator system to the collider, but in January, a mere 30% made the journey intact. "Really, until April we had no idea what the physical cause of this problem was," says [Stephen] Holmes [Head of Fermilab's Beams Division]. So, despite Fermilab's best efforts, "we topped out at about 40%. We were pretty much stuck."
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> In April, however, scientists at Fermilab figured out that the antiproton problem was caused by intrabeam scattering. "When the antiprotons are going around and around in the antiproton accumulator, they are confined to a very small space, and they are bouncing off each other," says Holmes. "This tends to heat the beam, making it get bigger. It wants to blow up." Scientists had anticipated problems, but this effect was worse than expected.

[5] C. Seife***, Science***, Vol. 297, p. 757 (2002).

> "Now a 2-week shutdown in June might have solved the antiproton problem," Holmes says. While the accelerator was turned off, engineers improved the beam cooling system and refocused the magnetic optics that keeps the beam tight. Now about 50% to 60% of the antiprotons survive the trip to the accelerator, and the number is rising. With that roadblock removed, last week the Tevatron's luminosity surged to a record-setting $2.64 \times 10^{31}$ inverse square centimeters per second……"

Not long after Bj and I completed our work, Alvin Tollestrup informed me that he was looking for ways to simplify Piwinski's scattering function so that he could use it for studying upgrades to the Tevatron lattice. Aside from phase space factors, Piwinski's scattering function gives the rise times for the three beam dimensions and involves taking an integral of trigonometric functions times the exponential of trigonometric functions. Alvin is one of those rare physicists who can design both detectors and accelerator lattices. As he tinkered with lattice designs for the first Tevatron upgrade, he wanted to know the effects of intrabeam scattering on luminosity lifetime for changes to the lattice, without waiting long periods of time running computer programs. He asked if I would be interested in collaborating with him to obtain simple analytic closed expressions for the Piwinski scattering function, since that would greatly reduce the computer time required. Given the 1 TeV energy of the protons and antiprotons at the Tevatron, we had the advantage of using the Month-Weng discussion[6] of the Piwinski formalism and applying it to asymptotically large energies. Indeed, we did achieve success in completely integrating the Piwinski scattering function to arrive at a simplified new high energy scattering function useful for predicting the evolution of luminosity with time for the Tevatron and future generations of hadron

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[6] M. Month and W.-T. Weng, AIP Conf. Proc. No. 105, p. 124, AIP, New York, NY (1983).

colliders.[7] One of our Fermilab colleagues, David Finley, used our results and my paper with Bj to study the effects of intrabeam scattering on the proposed Tevatron upgrade's integrated luminosity and demonstrated that, while intrabeam scattering effects were visible, they did not negate gains made by adjusting other accelerator parameters.[8]

Approximately 15 years passed before I engaged with intrabeam scattering again. I became interested in the next generation electron-positron collider and joined the team that led to the International Linear Collider (ILC) collaboration. My LBNL colleagues, William Barletta, Miguel Furman and Andy Wolski invited me to spend some time with Andy working on intrabeam scattering for the ILC damping rings. KEK had already begun studies in their prototype damping ring called the Accelerator Test Facility (ATF). Karl Bane at SLAC had spent some time here at the ATF and had proposed an elegant ansatz for connecting the Piwinski formalism to Bj's and my formulae at high energies, which is quite applicable to the 1.28 GeV electron beams at the ATF damping ring.[9] Bane called it the ***Modified Piwinski*** solution. Kiyoshi Kubo, one of the lead researchers at the ATF, Andy and I succeeded in combining my work with Tollestrup with Bane's ansatz to arrive at a ***Completely Integrated Modified Piwinski*** solution to intrabeam scattering.[10] We then used it to obtain excellent numerical analyses for the ATF data.

The work by Bj and me, using a quantum field theory approach to intrabeam scattering, is an excellent example of the importance of cross-fertilization. Bj

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[7] S. Mtingwa and A. Tollestrup, Fermilab-Pub-89/224 (1987).
[8] D. Finley, Fermilab-TM-1646 (1989).
[9] K. Bane, Proc. of the 8th EPAC, p. 1443, Paris (2002).
[10] K. Kubo, S. Mtingwa and A. Wolski, Phys. Rev. Spec. Topics – Accel. and Beams , **8**, 081001 (2005).

recalls that, in those days, it was especially easy for him to cross over from particle physics to accelerator physics. He did not have to go through an annual performance review, demonstrating how his activities were contributing to the goals of the elementary particle physics theory group, as defined by some set of oversight committees. Nowadays, at least in the U.S., it is harder to engage in crossover research or in research topics outside of the mainstream.

For the last set of comments, I would like to reflect on the role that accelerator physics has had on my desire to improve the state of science and technology in Africa and other parts of the developing world. In 1988, the late Nobelist, Abdus Salam, brought a group of scientists and mathematicians from Africa and the United States together at the International Centre for Theoretical Physics (ICTP) in Trieste to foster collaborations between the two communities. Fig. 4 shows a group photo of that meeting. At a subsequent meeting in 2000, I proposed that we undertake a major effort to bring a synchrotron light source to Africa. We decided that that may be a bit too ambitious, but that as a first step we should do something to improve laser science and technology in Africa. With that mandate, I connected with major science and technology proponents in Africa, most notably Philemon Mjwara, who at the time was Centre Manager of South Africa's National Laser Centre (NLC) and is presently Director General of South Africa's Department of Science and Technology. He led South Africa's co-winning bid with Australia to host the Square Kilometre Array (SKA), which will become the world's largest radio telescope. With our colleagues, we established the ***African Laser Centre (ALC)*** to enhance laser research and training in Africa. The ALC is headquartered at the NLC in Pretoria and consists of over 30 laser laboratories in many African countries as depicted in Fig. 5. I chaired the writing of the 2002 document, ***A Strategy and Business Plan for an African Laser Centre***, wherein we included an

African synchrotron light source as a long-term goal, making this the first call for an international synchrotron light source in Africa. The official launch of the ALC occurred during November 2003 in Johannesburg during a meeting of the New Partnership for Africa's Development (NEPAD) Conference on Science and Technology for Development. NEPAD declared the ALC to be one of its Centres of Excellence. Fig. 6 is a group photo of the ALC organizers. Figs. 7-9 contain photos of various ALC workshops and conferences. Fig. 10 provides a number of ALC accomplishments during the 2006-2013 period.

When my colleagues in Africa inquire as to the kind of laser work that I do, I must tell them that I know little about them. They look really confused. To resurrect their respect for me, I always point to my ambition to see a synchrotron light source in Africa. That seems to satisfy most. South Africa is the furthest along in using advanced light sources, mostly at the European Synchrotron Radiation Facility (ESRF) in Grenoble. Herman Winick and I attended a synchrotron science workshop during December 2011 in Pretoria convened by the South African Institute of Physics and South Africa’s Synchrotron Research Roadmap Implementation Committee. Fig. 11 is a group photo of attendees. The Director General of the ESRF, Francesco Sette, attended and urged South Africa to become a formal member of the ESRF. After the meeting, I chaired the writing of the document, ***Strategic Plan for Synchrotron Science in South Africa***. One of the proposals was for South Africa to adopt Sette’s request, which it did, and on May 21, 2013, South Africa officially became the 20$^{th}$ dues-paying member country of the ESRF. Fig. 12 contains a photo of the signing ceremony.

Fig. 13 depicts the locations of light sources in the world and shows that Africa is the only habitable continent in the world without one. To spur the effort on for a light source in Africa, Herman Winick and I wrote a paper entitled, ***A Synchrotron Radiation Research Facility for Africa***,[11] which gave a foundation to the effort that convened the first ***African Light Source (AfLS) Conference and Workshop*** at the ESRF during November 16-20, 2015. Led by Simon Connell from the University of Johannesburg, the meeting had approximately 100 participants and Fig. 14 shows a few of them. The meeting generated short-, medium- and long-term goals, as well as adopted a set of resolutions, dubbed the Grenoble Resolutions, provided in Appendix 2 that provide the ***WHY*** for an AfLS.

A final initiative that I have had the honor of collaborating on, mainly with Sandro Scandolo of International Union of Pure and Applied Physics (IUPAP) and International Centre for Theoretical Physics (ICTP) and Michele Zema of the International Union of Crystallography (IUCr), with considerable input from Herman Winick and my prior Antiproton Source colleague, Ernie Malamud, is called ***Lightsources for Africa, the Americas, and Middle East Project (LAAMP)***. The Americas part of the project focuses on Mexico and the Caribbean. The goal is to enhance advanced light source science in more regions of the world. Some 25 institutions and organizations have agreed to collaborate, including light sources, ICTP, UNESCO, and international physics societies. In particular, we are extremely pleased that Professor Hitoshi Abe is representing KEK's IMSS in collaborating with us. We just received a 300K Euro grant from the International Council for Science (ICSU) to both IUPAP and IUCr and are formally kicking off our programs this summer, with perhaps the two most important being sending students and researchers to various light sources for training and developing ***Strategic Plans*** for each region, leading to the possibility of constructing light

[11] S. Mtingwa and H. Winick, http://www.lightsources.org/news/2014/09/05/synchrotron-radiation-research-facility-africa (2014).

sources in regions that do not already have one.

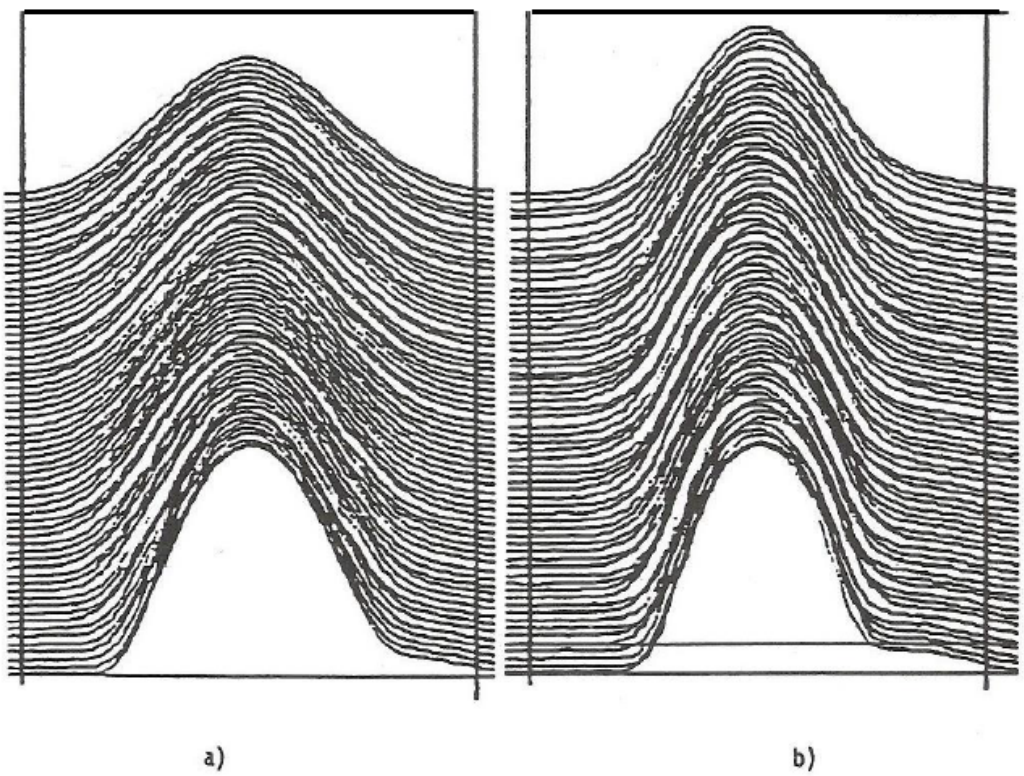
These initiatives have brought me full circle back to intrabeam scattering. The new 4$^{th}$ generation synchrotron light sources make use of a new magnet design called the ***multibend achromat (MBA)***, which was invented by researchers in Sweden and implemented at their new MAX IV light source. That and other light sources implementing this new technology are shown in Fig. 15. Vertical electron beam emittances are naturally quite small. In comparison, horizontal emittances tend to be many times larger. The smaller the horizontal electron emittance, the brighter photon beams tend to be that they generate. Fig. 16 shows proposed electron beam horizontal emittances and energies. Fig. 17 shows the resultant photon brightness. Operating at horizontal and vertical emittances of 320 and 8 picometers, respectively, Fig. 18 shows the Max IV % horizontal beam emittance growth with and without devices called Landau Cavities (LCs), which help to mitigate intrabeam scattering effects.

Fig. 18 shows that, more and more, intrabeam scattering will be a stringent limitation that must be overcome in future light sources. It is a dominant heating mechanism for all high intensity beams, constraining luminosity lifetimes in hadron colliders and determining equilibrium emittances in antiproton accumulators, electron and positron damping rings, and synchrotron light sources. When my colleagues in Africa ask me what laser science I do, I have to say none. When they ask me what synchrotron light source beamline technique I use, I still have to say none. However, because of my work on intrabeam scattering, I can now say that I do not use the synchrotron light source beamlines, but I do work on squeezing the last photons out of them. And that seems to satisfy them.

As a high energy physicist, I am proud that our community has invented the synchrotrons used at light sources. They are revolutionizing so many disciplines, from biology, drug discovery, materials science, physics, chemistry to paleontology and cultural heritage studies. As a community, we need to add this to our list of technological breakthroughs that have changed the way we live, along with the World Wide Web and various medical imaging techniques. We need to shout it to the heavens!!

In conclusion, when Bj and I undertook our work on intrabeam scattering, we were simply trying to understand its effect on Fermilab Antiproton Source's ability to accumulate antiprotons. Little did we know that over the years intrabeam scattering would become so crucial for the operation of so wide a class of accelerators, even assisting in the discoveries of the top quark and Higgs particle and helping to revolutionize so many disciplines at synchrotron light sources.

## Coulomb Scattering of Particles within a Beam

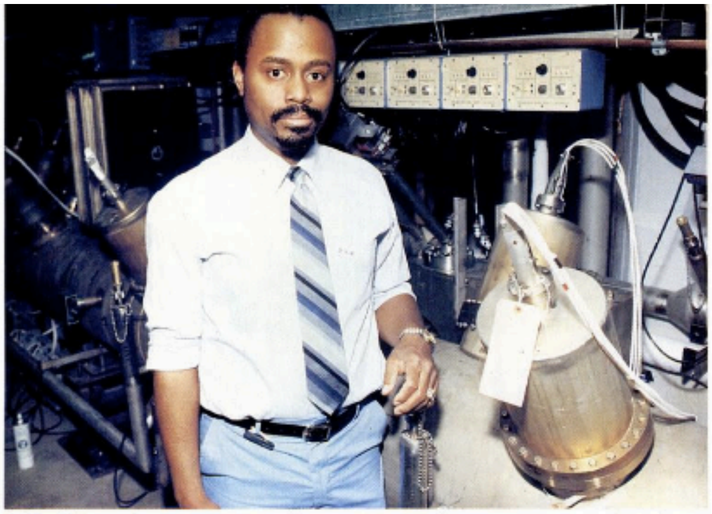



**Measurements Made at 15 min Intervals in the CERN SPS of the Longitudinal Distribution of**

**a) A Proton Bunch ($N^+ = 1.5 \times 10^{11}$)**

**b) An Antiproton Bunch ($N^- = 1.2 \times 10^{10}$)**

**Figure 1**



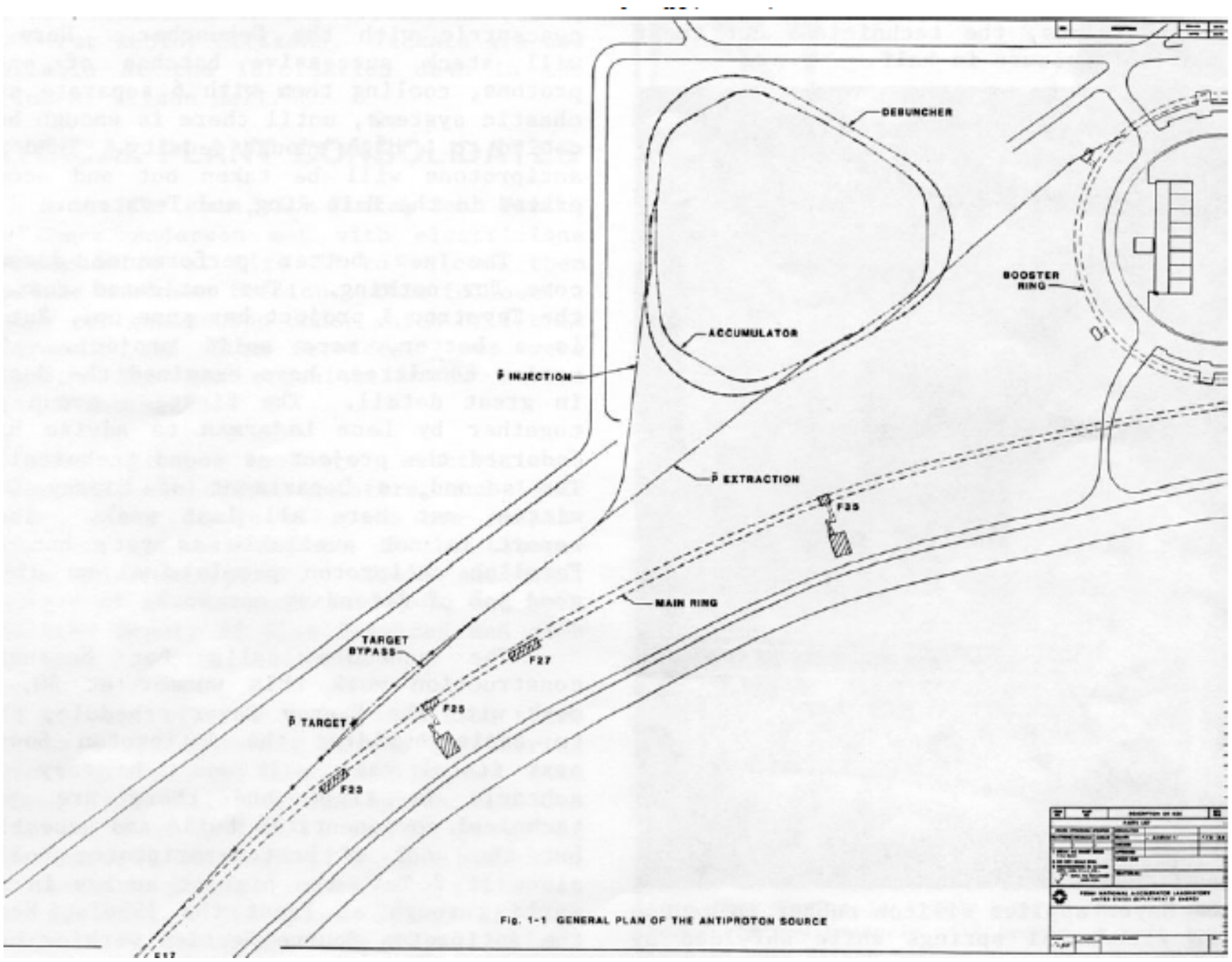
**Dr. Sekazi Mtingwa**, shown near a superconducting magnet, is a physicist at Fermi National Accelerator in Batavia, Ill. He's currently working on what may be the most powerful accelerator in the U.S.

**DR. SEKAZI MTINGWA**'s key to the future could lay in unlocking the very origin of the universe. "High-energy physics is really the area of physics that deals with the simplest particles in nature," says Dr. Mtingwa, 35, a physicist at the Fermi National Accelerator Laboratory in Batavia, Ill. "The substances around us are composed of molecules; molecules are composed of atoms, and atoms are sort of the basic building blocks of nature. But even atoms have a nucleus (made up of protons and neutrons) and electrons that travel around them," Dr. Mtingwa says. His mission is to smash those atoms by stripping them of electrons, then circulating the protons at high speeds around a special "accelerator," striking them against targets and then studying the new combinations that result. It is the curiosity about what lies beyond even the smallest particle combination uncovered to date that is spurring a debate in the physics world about the need to build a Superconducting Supercollider (SSC), an atom-smasher with power currently unattainable. Physicists argue the SSC could uncover the link for understanding the origin of the universe through the new particles it would reveal. The price tag of $6 billion is slowing government approval for building the giant accelerator. Dr. Mtingwa is working on Fermilab's Tevatron I (scheduled to be operational in August), which now is considered the most powerful accelerator in the U.S. The Tevatron I has 1,000 superconducting magnets in a 20-foot-deep tunnel and is considered a forerunner of the SSC. The Tevatron I will collide protons and artifically created antiprotons at energy levels equivalent to one trillion electron volts. What does all this mean? Dr. Mtingwa and other physicists are not sure yet. "This is really the frontier of physics," says the Princeton Ph. D. and former Ford Fellow. "The more you probe into this particular subatomic world, the more building blocks you find." One thing he is sure of, however, is that fans of the futuristic television show *Star Trek* won't be seeing anyone reduced to particles and "beamed" through space anytime soon.

**Sekazi Mtingwa Featured in Ebony Magazine**

**(Correction to Caption: Mtingwa is standing next to a stochastic cooling tank.)**

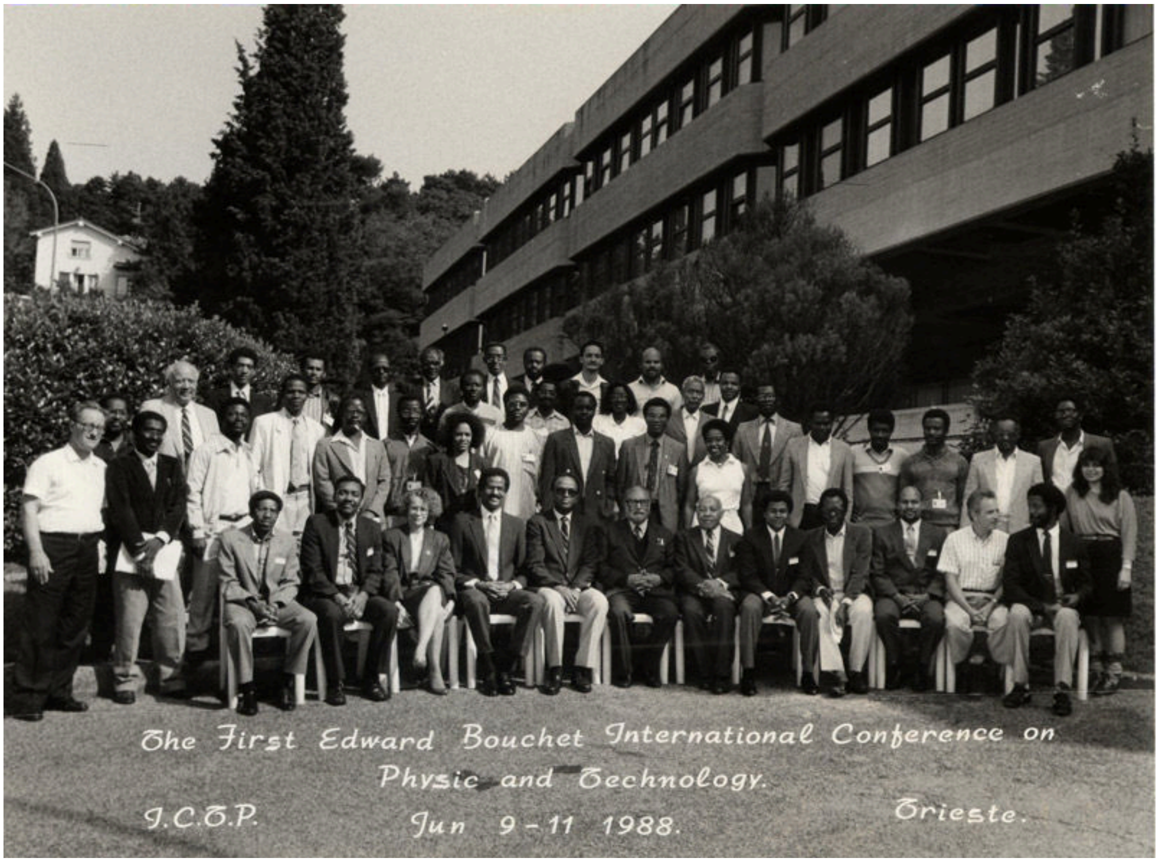
**Figure 2**




**Antiproton Source**

**(Courtesy of Fermilab)**

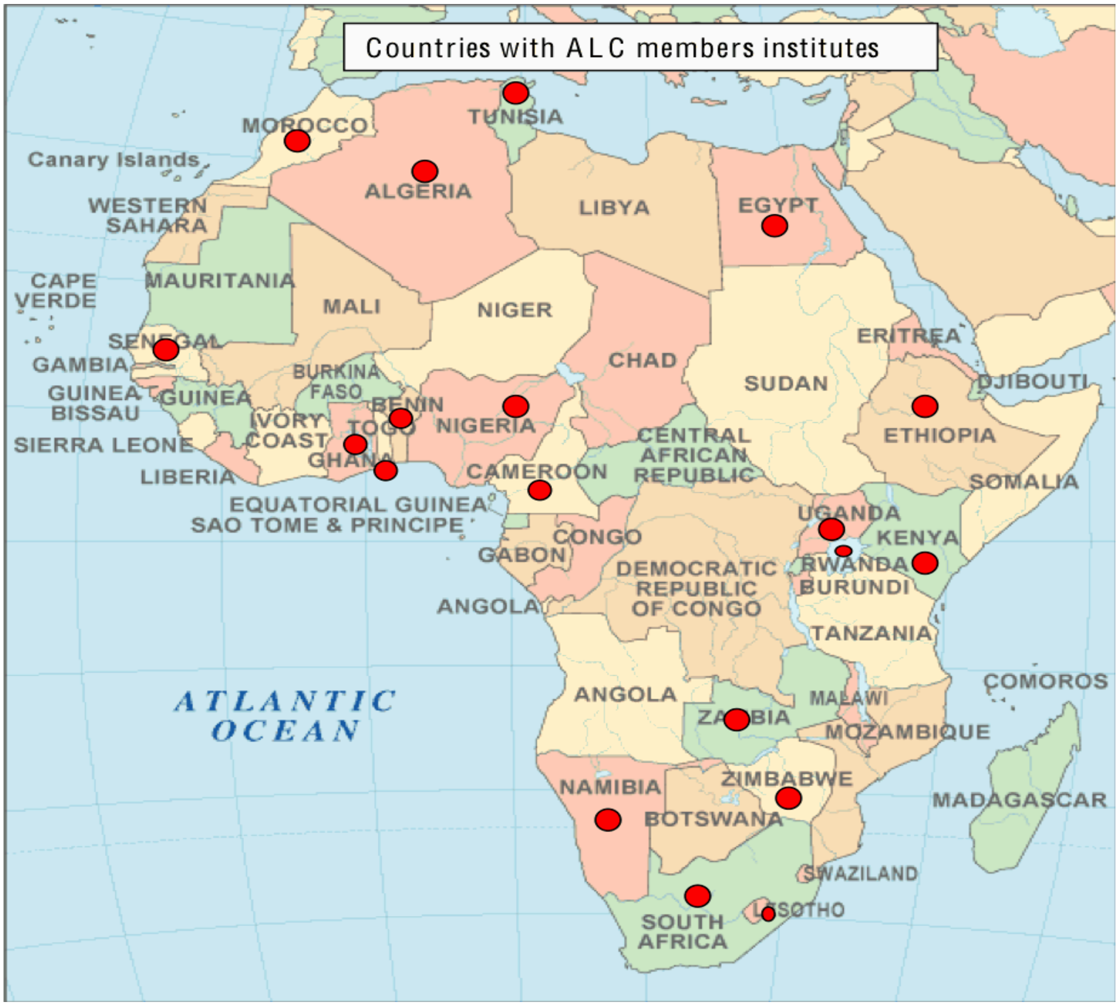
**Figure 3**




**Group Photo of the 1st Edward Bouchet Conference**

**(Figure Courtesy of ICTP)**

**Figure 4**




**Counties with ALC Member Institutions**

**(Figure Courtesy of the African Laser Centre)**

**Figure 5**

**Organizers of the African Laser Centre**
**Pretoria, South Africa**
**November 2003**

**Figure 6**

**5th Annual ALC Student Workshop**
**Namibia 2012**

**Figure 7**


**2nd US-Africa Advanced Studies Institute**
**iThemba LABS**
**Outside Cape Town, South Africa**
**November 2007**

**Figure 8**

**3rd US-Africa Advanced Studies Institute**
**Cairo, Egypt**
**November 2008**

**Figure 9**

| Output | Quantity | Comments |
|---|---|---|
| Projects supported | 87 | A total of 87 research collaborations between a South African team and other African research teams elsewhere on the African continent have been supported up to. This represents 87 grants. |
| Publications in refereed journals | 151 | Annual Report for period 2006 – 2013 |
| Popular journal articles | 13 | Annual Report for period 2006 - 2013 |
| Publications in conference proceedings | 210 | Annual Report for period 2006 - 2013 |
| Chapters in books | 12 | Annual Report for period 2006 - 2013 |
| Theses completed | 59 | Annual Report for period 2006 - 2013 |
| Masters scholarships awarded | 38 | This represents total the number of scholarship grants that were awarded within the period 2007-2013. |
| PhD scholarships awarded | 78 | This represents the total number of scholarship grants that were awarded within the period 2007-2013. |
| Training events (workshops/conferences/ symposia, short courses) supported | 33 | 2005-2013 |
| Number of students trained at workshops, symposia and short courses | 1249 | Number of beneficiaries to ALC training since inception to 2013 |
| Masters Students supported | 141 | This represents the total number of MSc students working within the supported collaboration projects. |
| PhD Students supported | 165 | This represents the total number of PhD students working within the supported collaboration projects. |

**ALC Accomplishments during 2006-2013**

**Figure 10**


**Synchrotron Science Workshop**
**Pretoria, South Africa**
**December 1-2, 2011**

**Figure 11**

**(Photo courtesy of the South African Institute of Physics)**

**From left to right front row: Francesco Sette, ESRF Director General; Nithaya Chetty, Group Executive for Astronomy, South Africa's National Research Foundation; Luis Sanchez Ortiz, ESRF Director of Administration.**

**From left to right back row: Bauke Djikstra, ESRF Director of Research; Thomas Auf der Heyde, Deputy Director General, South Africa's Department of Science and Technology; Itziar Echeverria, ESRF DG Office; Tshepo Ntsoane, Chairman of South Africa's Synchrotron Research Roadmap Implementation Committee (SSRIC); Simon H. Connell, University of Johannesburg.**

**South Africa Joins the ESRF**
**Grenoble, France**
**May 21, 2013**

**Figure 12**

**(Photo courtesy of the ESRF)**

**Locations of World Synchrotron Light Sources**

**Figure 13**

**(Figure courtesy of lightsources.org)**


**Several Researcher & Student Participants**
**1st African Light Source Conference & Workshop**
**ESRF, Grenoble**
**November 2015**

**Figure 14**

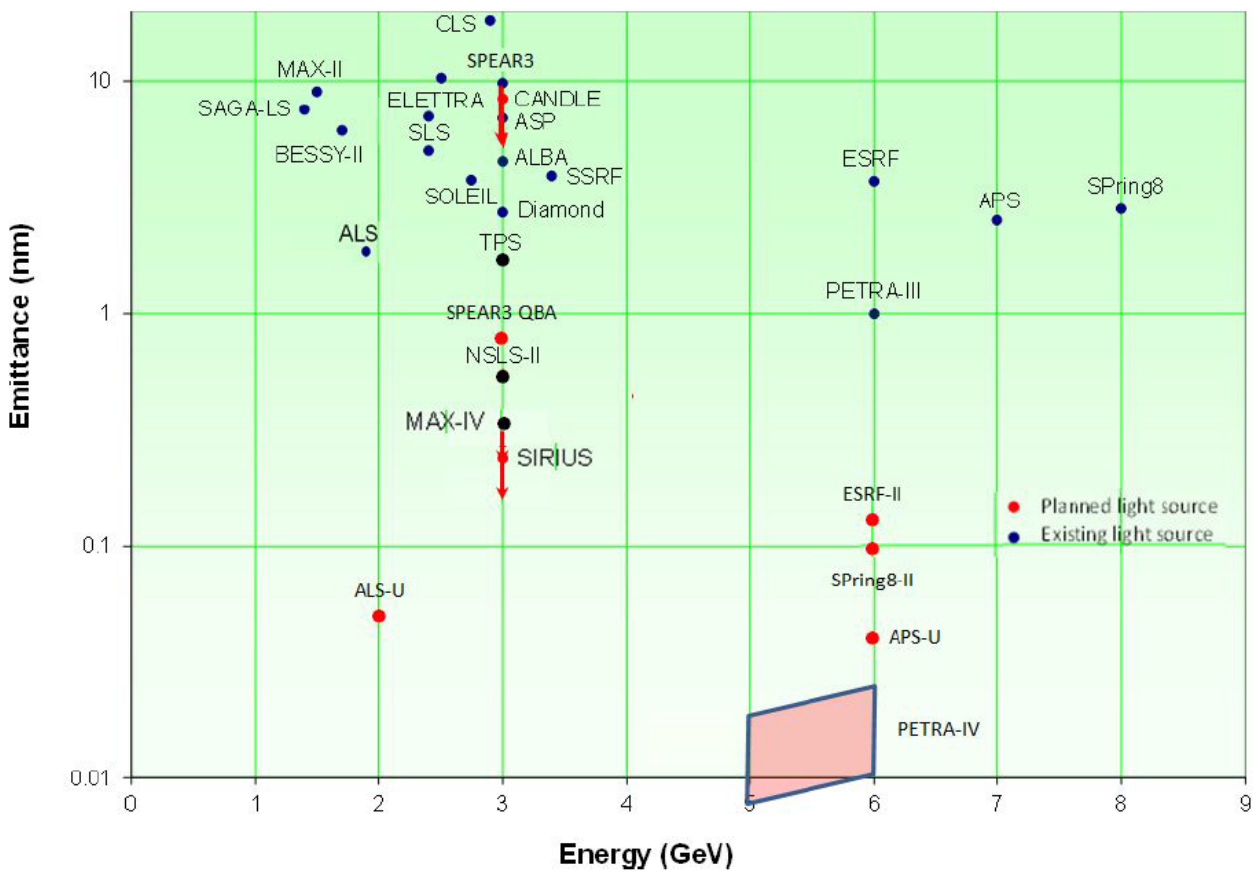
**((Figure Courtesy of the ESRF)**


**World Light Sources Implementing the New Multibend Achromat Technology**

***from***
***Accelerator Physics Challenges in the Design of Multi-Bend-Achromat-Based Storage Rings***
***M. Borland, ANL***
***R. Hettel, SLAC***
***S. C. Leemann, MAX IV Laboratory***
***D. S. Robin, LBNL***
***Contribution to NAPAC 2016, Chicago, IL, USA, October 2016***

**Figure 15**

**(Figure Courtesy of the MAX IV Laboratory)**

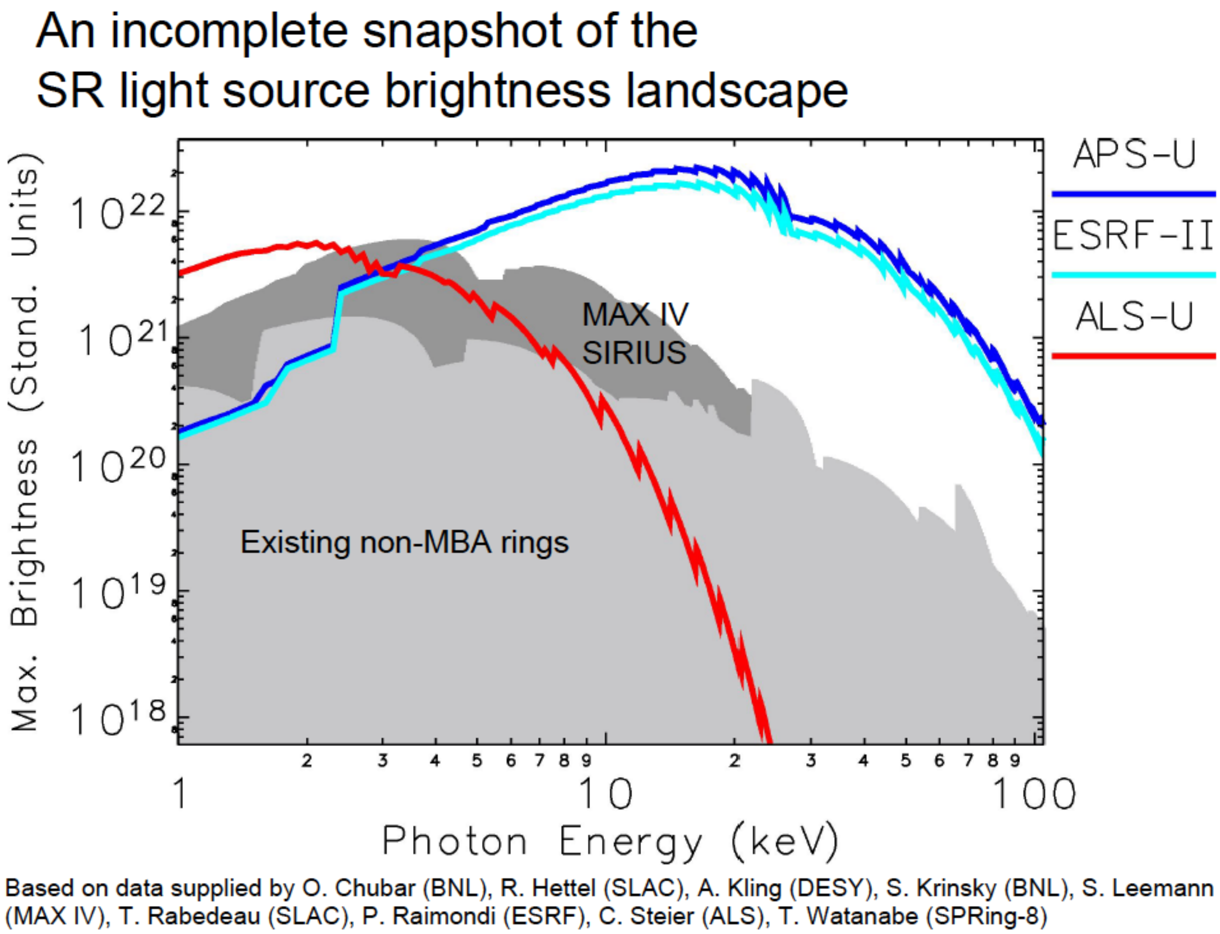



**Horizontal Beam Emittances at World Light Sources**

***from***
***Accelerator Physics Challenges in the Design of Multi-Bend-Achromat-Based Storage Rings***
***M. Borland, ANL***
***R. Hettel, SLAC***
***S. C. Leemann, MAX IV Laboratory***
***D. S. Robin, LBNL***
***Contribution to NAPAC 2016, Chicago, IL, USA, October 2016***

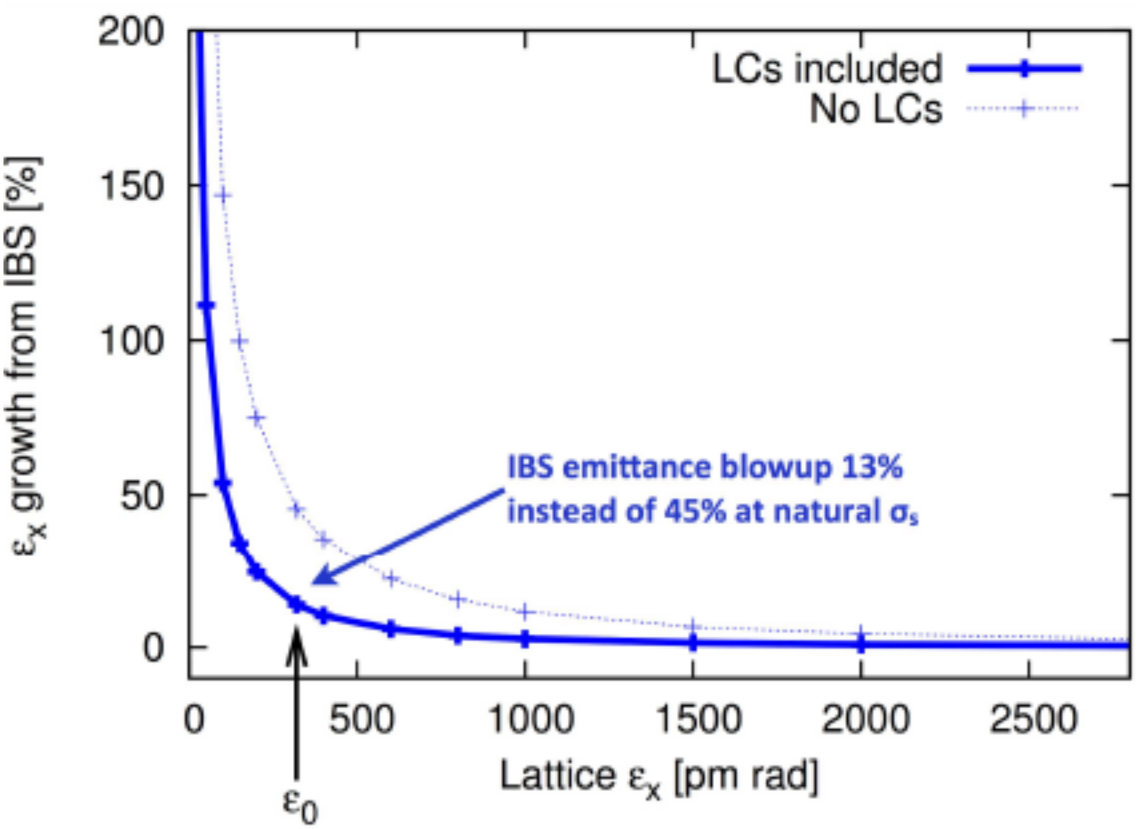
**Figure 16**

**(Figure Courtesy of the MAX IV Laboratory)**




***from***
***Accelerator Physics Challenges in the Design of Multi-Bend-Achromat-Based Storage Rings***
***M. Borland, ANL***
***R. Hettel, SLAC***
***S. C. Leemann, MAX IV Laboratory***
***D. S. Robin, LBNL***
***Contribution to NAPAC 2016, Chicago, IL, USA, October 2016***

**Figure 17**
**(Figure Courtesy of the MAX IV Laboratory)**




**% Horizontal Beam Emittance Growth due to Intrabeam Scattering**
**(LCs=Landau Cavities)**

***from***
***Accelerator Physics Challenges in the Design of Multi-Bend-Achromat-Based Storage Rings***
***M. Borland, ANL***
***R. Hettel, SLAC***
***S. C. Leemann, MAX IV Laboratory***
***D. S. Robin, LBNL***
***Contribution to NAPAC 2016, Chicago, IL, USA, October 2016***

**Figure 18**

**(Figure Courtesy of the MAX IV Laboratory)**

# APPENDIX 1

## Historical Notes for IBS

1) H. Bruck, J. Le Duff, Lab. Acell. Lin., Orsay, Rap.Techn (1964)

2) C. Pellegrini, Proc. Int. Symposium on Elec. Pos. Storage Rings (1966)

**Investigation of the transfer of oscillation energy from one direction to another**

3) A. Piwinski, Proc. 9th Int. Conf. on High Energy Acc. SLAC (1974)

**Investigation of energy transfer between all three directions taking into account the corresponding energy losses**

4) K. Huebner, D. Moehl, F. Sacherer, CERN, computer code (1977)

**Calculation of rise time due to IBS including the derivations of amplitude function and dispersion (A. Piwinski, F. Sacherer)**

5) J. D. Bjorken, S. K. Mtingwa, Particle Acc. 13, 115 (1983)

**A completely new and elegant method for the calculation of the rise times**

# APPENDIX 2

*Grenoble Resolutions*

1. ***Advanced light sources are the most transformative scientific instruments similar to the invention of conventional lasers and computers.***

2. ***Advanced light sources are revolutionizing a myriad of fundamental and applied sciences, including agriculture, biology, biomedicine, chemistry, climate and environmental eco-systems science, cultural heritage studies, energy, engineering, geology, materials science, nanotechnology, palaeontology, pharmaceutical discoveries, and physics, with an accompanying impact on sustainable industry.***

3. ***The community of researchers around the world are striving collaboratively to construct ever more intense sources of electromagnetic radiation, specifically derived from synchrotron light sources and X-ray free-electron lasers (XFELs), to address the most challenging questions in living and condensed matter sciences.***

4. ***The African Light Source is expected to contribute significantly to the African Science Renaissance, the return of the African Science Diaspora, the enhancement of University Education, the training of a new generation of young researchers, the growth of competitive African industries, and the advancement of research that addresses issues, challenges and concerns relevant to Africa.***

5. ***For African countries to take control of their destinies and become major players in the international community, it is inevitable that a light source must begin construction somewhere on the African continent in the near future, which will promote peace and collaborations among African nations and the wider global community.***