Research in Accelerator Physics

Alexander Chao 趙午，SLAC

Tsing Hua Physics
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What is accelerator physics?

> This field may not be familiar. One reason is that its wide significance is appreciated only in the last 20 years. Another is that it is typically not taught in the universities.

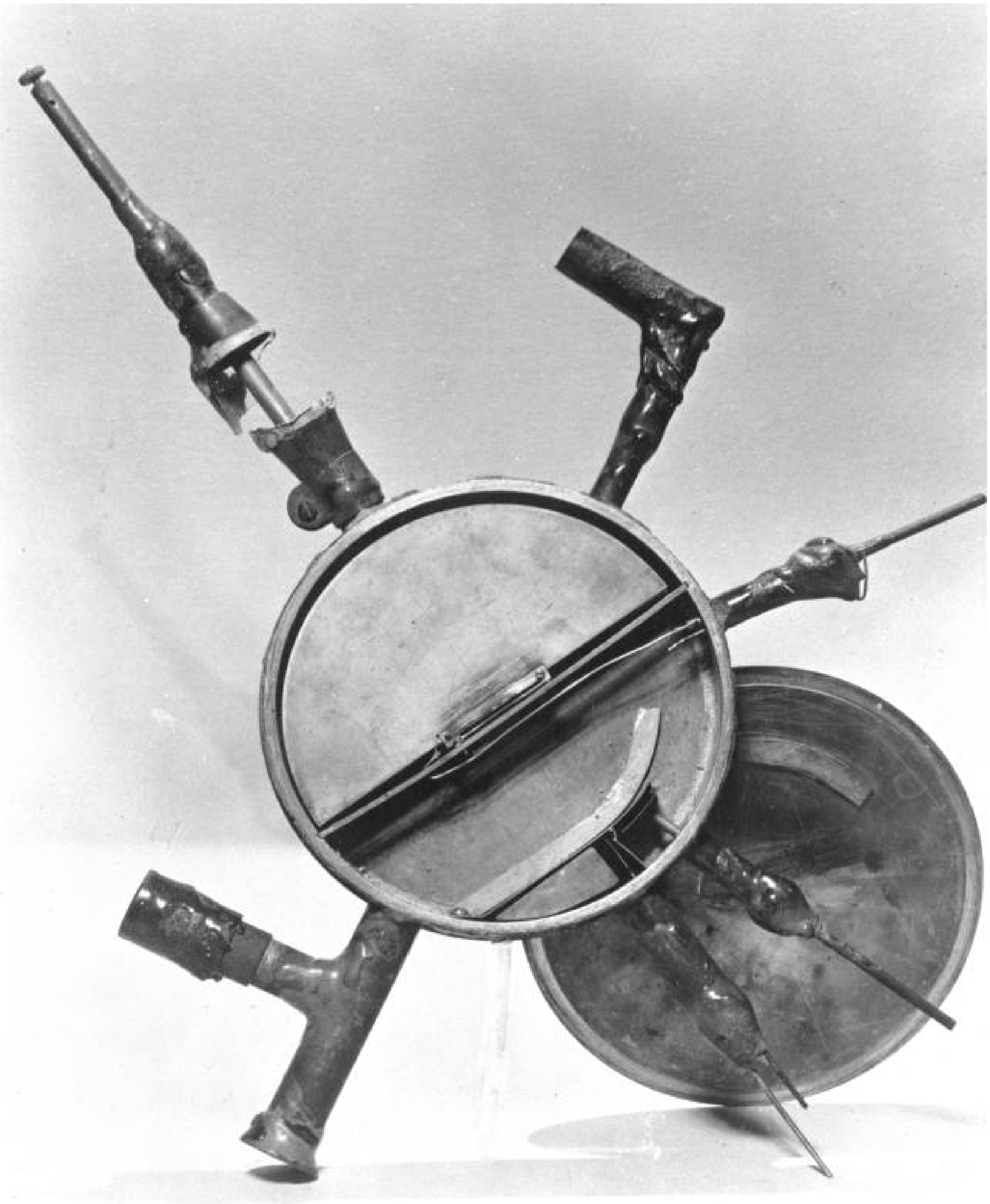
Accelerator physics is a branch of physics that studies particle beams in accelerators. Its special (seemingly contradictory) characteristics are:

> Accelerators have wide applications
> Accelerator physics is a deep research field by itself

The field started in 1932, when Cockcroft and Walton built the first high energy electrostatic accelerator.

1933 E.O. Lawrence’s cyclotron.

Today, the largest accelerator is the Large Hadron Collider (LHC) at CERN for the study of high energy physics.



Since 1932, the equivalent beam energy of accelerators has been increasing exponentially by x 10 every 7 years, and x 10^{12} in 70 years.

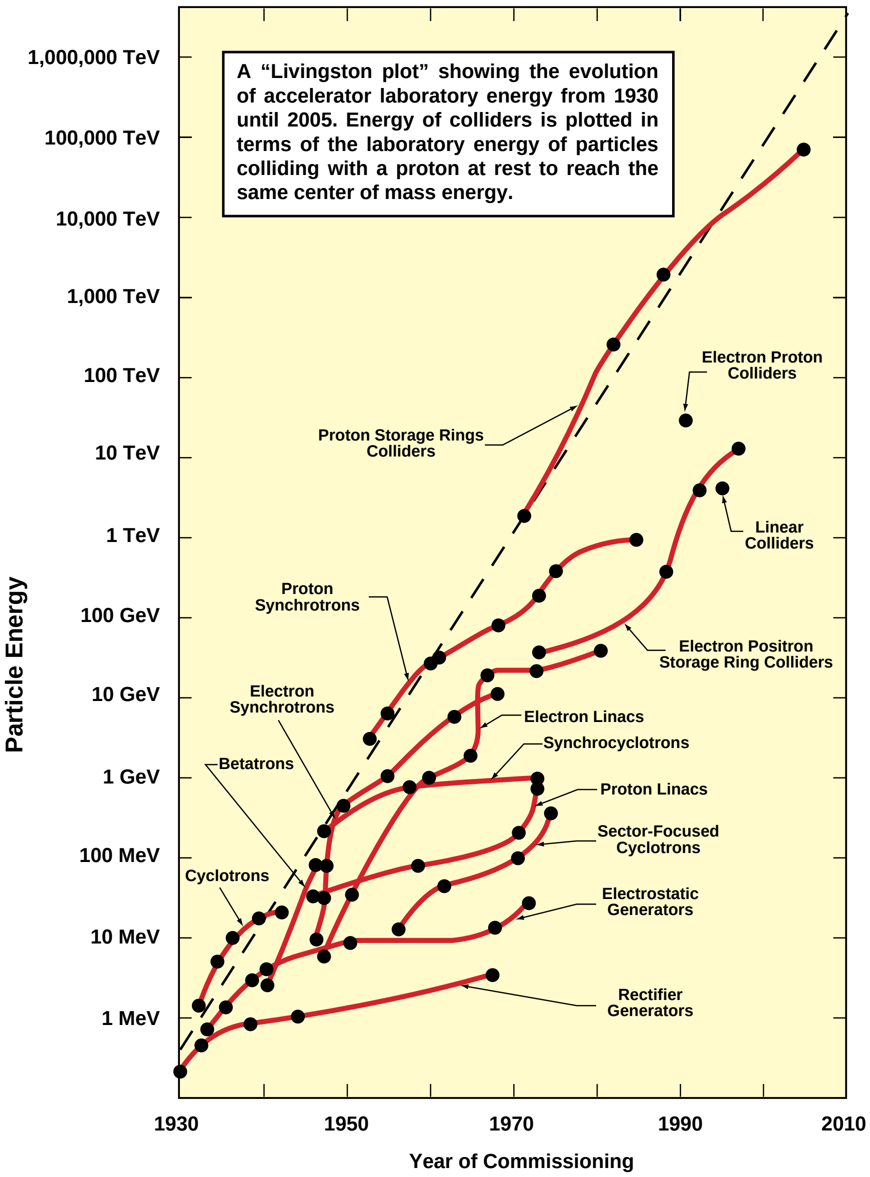
See Livingston chart.

> When one technology ran out of steam, an innovation rose to the occasion. The field of accelerator physics has been very active.

Nobel prizes
- 1939 Lawrence
- 1951 Cockcroft & Walton
- 1968 Alvarez
- 1984 Van de Meer

However, …

Critical question for high energy physicists:
Is the trend of Livingston exponential going to continue?



A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

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Perspectives

The field started for nuclear physics. Made a transition to high energy physics in the 1960-70s.

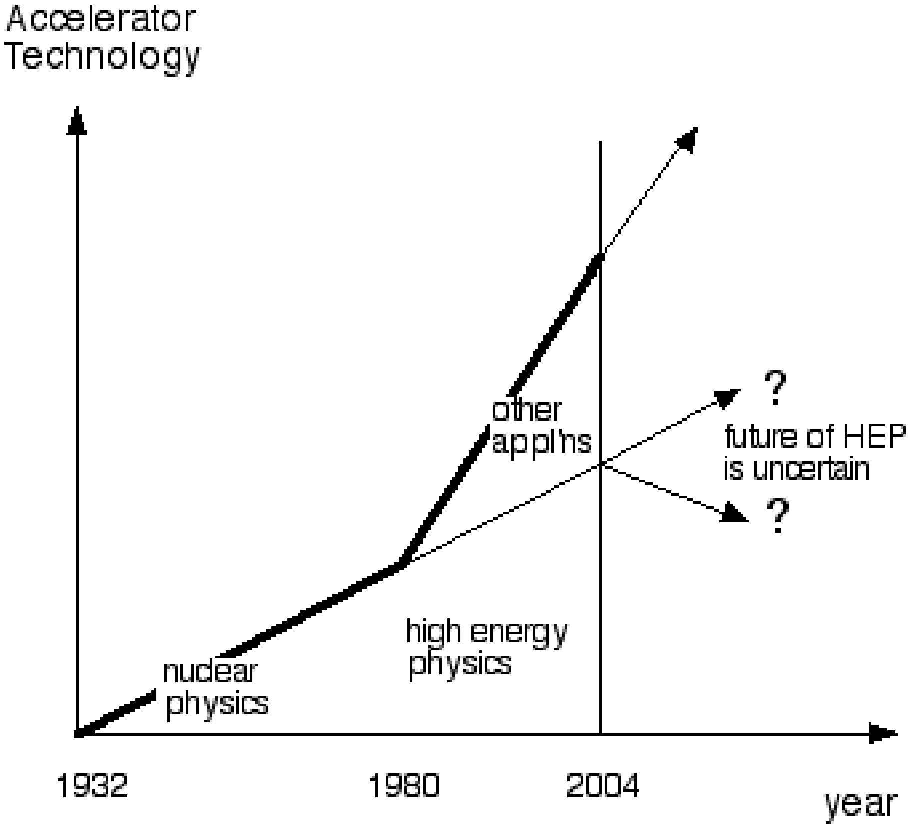
Accelerator size grew rapidly from 1.2 MeV cyclotron 1933 to 7 TeV LHC in 2006.

Cost grew rapidly also, although cost per GeV is decreasing.

Desperately seeking an accelerator technology breakthrough. Otherwise high energy physics will end.

In the mean time, since 1980s, rapid technology growth is continuing in other applications. American Physical Society established a new Beam Physics Division in 1985, with 1200 members out of 40000 in APS. Europe, Japan, China followed in other forms.

The field is rapidly evolving and growing. This is a critical time of transition for accelerator physics.



Nonlinear Dynamics and Chaos

Collective Beam Instabilities

Advanced Acceleration Concepts

Other Topics

Nonlinear Dynamics and Chaos

Chaos is a phenomenon commonly observed in nonlinear dynamical systems. Storage rings constitute a particularly intricate nonlinear dynamical system for the study of chaos.

Particles are stored for 10^{10-11} revolutions in storage rings. In comparison, the earth has so far made only 10^{9} revolutions. It is not obvious that the earth motion is stable.

Chaos phenomenon imposes one of the key design criteria for storage rings.

Chaos and instability results from nonlinearities, e.g. nonlinear field errors in magnets.

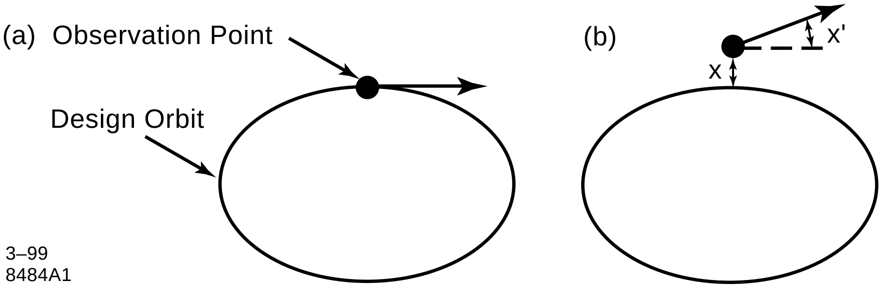
Would the small nonlinearities in magnets (10^{-4}) cause a slow growth of particle's oscillation amplitudes, and thus lead to their eventual loss in 10^{10-11} turns?

To minimize cost, one must build the magnets at their lowest tolerable degree of nonlinearity, while providing 10^{10-11}-turn lifetime of the beam. A misjudgment here can be a serious matter.

One might arguably say that the demise of the Superconducting Super Collider project originated from a misjudgment in its chaos analysis at one point, which in turn led to its first substantial cost escalation.

1. Dynamic aperture

For storage rings, one key question is “What is the dynamic aperture?” Dynamic aperture limitation comes from chaotic motion caused by too much nonlinearity in the accelerator. To provide a sufficiently large dynamic aperture is one of the key design criteria for storage rings.



A particle that starts on the design orbit returns to its starting point turn after turn.

A particle starting with a small deviation (x, x') does not return to its starting point. Its may

- stay confined => stable
- grow with time => unstable

The question: does the accelerator provide a stable environment for particles with deviations for $\tau = 10^{10}$ turns?

Note that accelerator physicists are not interested in $\tau = \infty$ which would be a very different question.

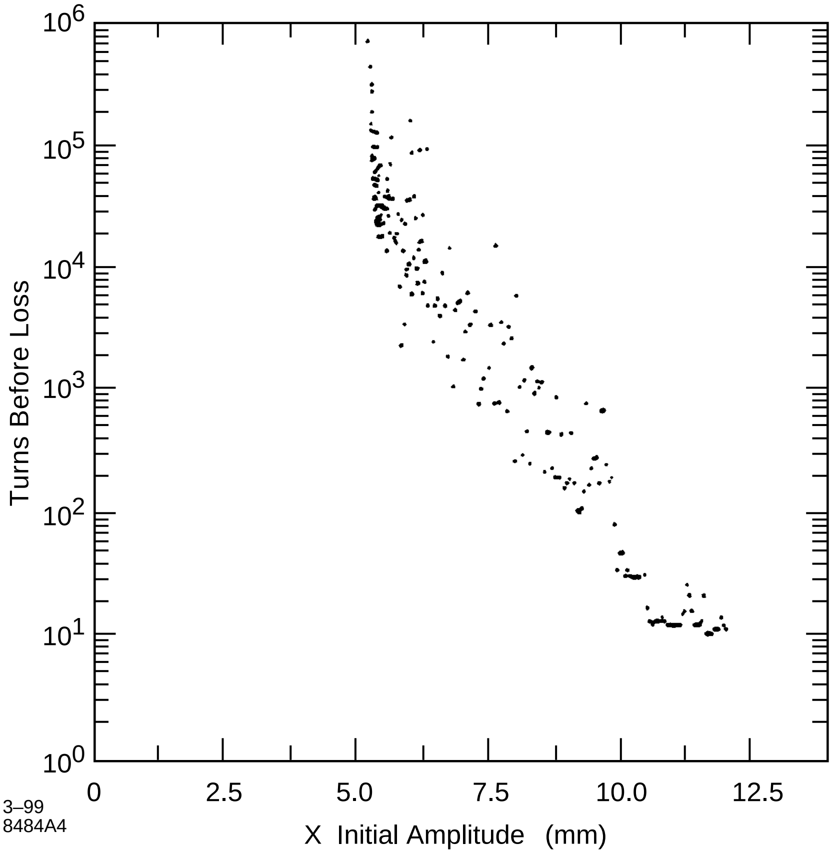
The maximum amplitude for stability is called the dynamic aperture.

One most notable example was the SSC.

Question: Given the nonlinearities in the magnets (10^{-4}), find the dynamic aperture.

Dynamic aperture is often found by computer simulation. Example for an SSC model:

Y.Yan 顏詒通, et al



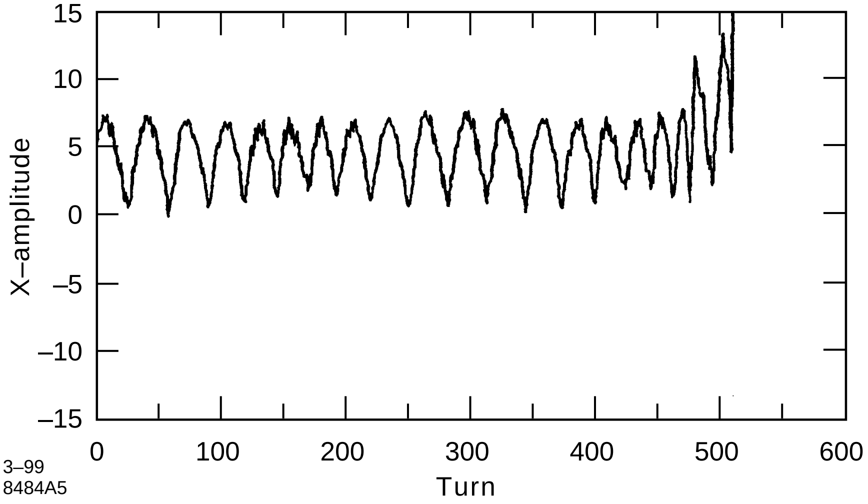
The survival time of a particle is plotted against the initial amplitude of the particle when it was launched in the simulation.

Lower the initial amplitude until the particle is stable
=> Dynamic aperture = 5 mm.

But simulations do not provide an understanding of the <u>nonlinear dynamics mechanism</u> that causes particle loss near the dynamic aperture. Close to the dynamic aperture, the underlying dynamics is extremely complex.

The last particle at 5mm for the SSC was lost near the 10^6-th turn. But this particle has been stable for 10^6 turns, and is suddenly lost in the last 30 turns without any apparent warning.

The last 512 turns of the particle:



What is the instability mechanism that does this?
Any “diffusion” effect is ruled out.

2. Nonlinear dynamics by combining analysis and advanced programming

Unfortunately, simulation is severely limited by computer capacity. The above SSC simulation (1993) took 200 CRAY hours for a mere 10^6 turns.

One way to overcome this problem is to use concatenation techniques. The entire accelerator is concatenated (and severely truncated) into a "one-turn map". Simulation is then done using this map. Simulating for 10^{10} turns becomes possible. But has one lost some physics by the concatenation?

Various concatenation techniques have been invented. Nonlinear dynamics research for accelerators in the past 15-20 years has seen great advances by combining two very powerful and exciting techniques:

Lie algebra: Alex Dragt 1983
Truncated power series algebra: Martin Berz, 1986

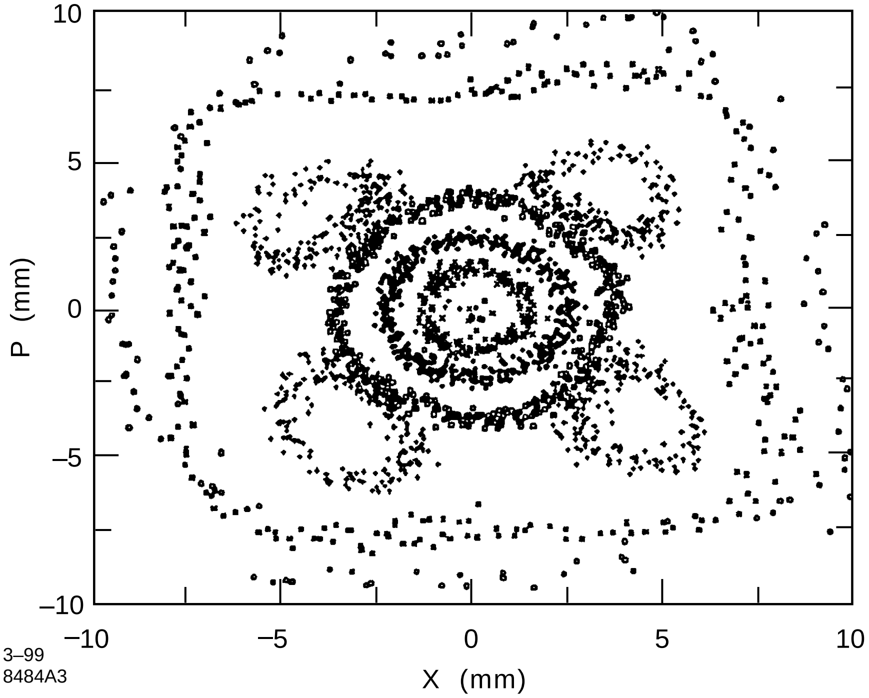
The combined application of Lie algebra and TPSA with advanced computational technology is an active research area in accelerator physics.
First application was at the SSC, 1986.

3. Nonlinear dynamics research using accelerators

Storage rings are good experimental tools for studying nonlinear dynamics and chaos physics.

Example: beautiful measured phase space of Indiana University Cyclotron when the tune ν ≈15/4.

S.Y. Lee 李世元, et al



From such measurements, one obtains detailed information on the nonlinear Hamiltonian of the accelerator system.

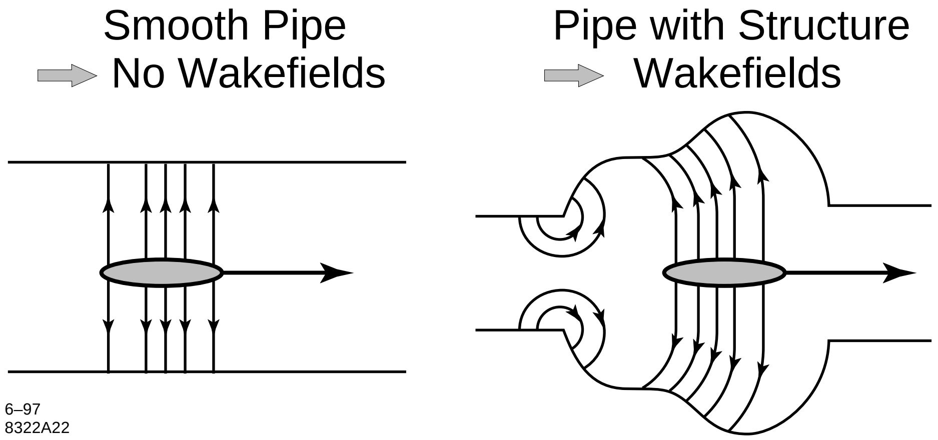
Collective beam instabilities

In this research area, accelerator physics overlaps with plasma physics. Many accelerator physicists were ex-plasma physicists.

However, there is an important difference:

beam self fields > external applied fields for plasma
beam self fields < external applied fields for accelerators
=>
First order perturbation techniques are applicable to accelerators.

Most of the beam self fields are in the form of wakefields, and are generated by beam-structure interaction.



Higher beam intensity => stronger wakefields => beam motion potentially unstable.

Over the years, accelerator physicists have observed, explained, and (mostly) cured several intricate instability mechanisms:

negative mass instability 1959
resistive wall instability 1960
beam break up instability in linacs 1966
head-tail instability 1969
microwave instability 1969
beam-beam limit in colliders 1971
potential well distortion 1971
anomalous bunch lengthening 1974
transverse mode coupling instability 1980
sawtooth instability 1993
electron beam-ion instability 1996
electron cloud instability 1997

~ one instability mechanism every 3 years

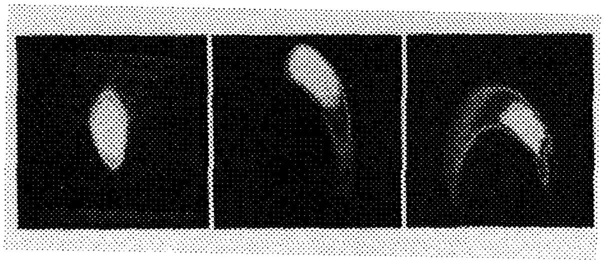
History shows new instabilities are discovered as we overcome the older instabilities and push for higher and higher beam intensities. The latest are found in the factory-class colliders.

As a result of this research, accelerators become more and more potent. Today, we speak of

- intense beams for fusion
- ultra-short intense bunches for X-ray free electron lasers
- even the not-yet-fully-understood beam-beam limit has allowed continued improvements on the luminosity of all high energy colliders

Example of beam break-up instability in the SLAC linac:

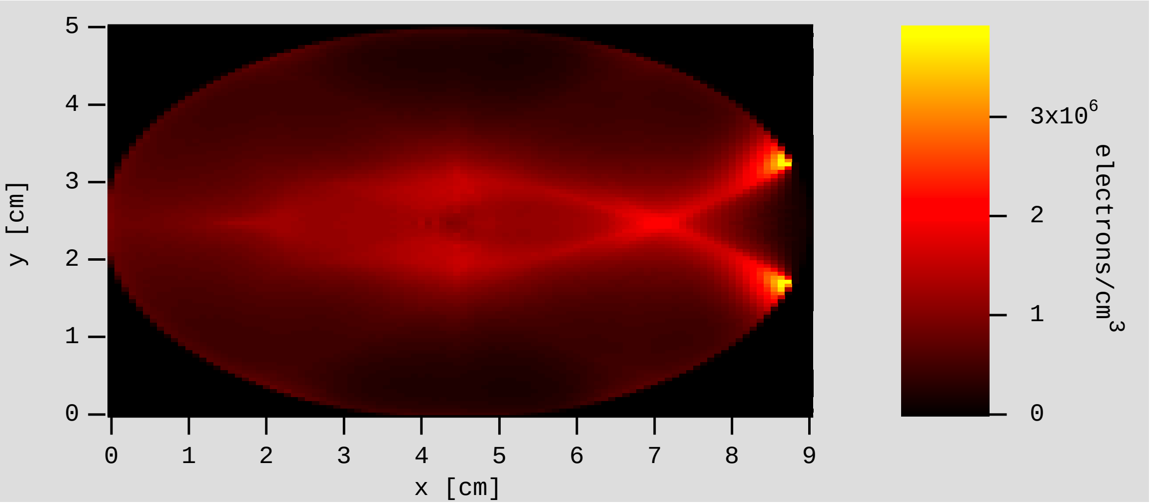
J. Seeman et al



Beam profiles for a well steered beam, a 0.5 mm oscillating beam, and a 1 mm oscillating beam.

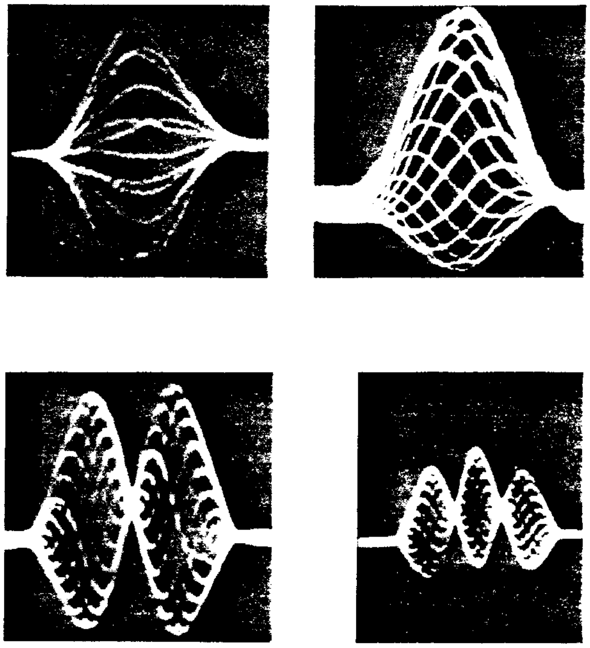
Example of electron cloud instability. Simulation for the positron ring for PEP-2:

M. Furman



Example of beautiful collective beam oscillation modes of a stored intense beam in the CERN PS:

J. Gareyte et al



Advanced acceleration concepts

Can the Livingston exponentiation continue indefinitely?

> In order to continue, we must reduce the cost per GeV. Over the years, even with drastic reduction on cost per GeV, accelerators have grown from table-top devices to gigantic projects.

This is a major concern for the future of high energy physics.

The current frontier technologies are running out of steam:

> Superconducting storage ring technology for proton colliders
> Linear collider technology for electron colliders
> Project costs ~ 2-3 B\$ ~ annual worldwide HEP expenditure

Much more drastic reduction of accelerator cost must be found in a not so distant future.

R&D of advanced acceleration concepts has become a critical issue for high energy physics. We are presently at a very early stage in this R&D activity.

There is no lack of ingenious ideas. On the contrary, there are many ideas

- from lasers to plasmas
- from high precision microwave structures to crystals.

So far, however, the efforts have not yet left the sense of developing a "gene pool". Examples:

- plasma beat wave accelerator
- plasma wake field accelerator, beam-generated
- plasma wake field accelerator, laser-generated
- plasma soliton accelerator
- plasma lens focusing
- laser-switch radial-transmissionline accelerator
- wake-field radial-transmissionline accelerator
- wake-field electron accelerator with proton driver
- acceleration at laser focus in free space
- laser grating accelerator
- laser dielectric medium accelerator
- inverse Cerenkov accelerator
- inverse free electron laser accelerator for electrons
- inverse free electron laser accelerator for protons in a modulated crystal
- cyclotron resonance laser accelerator
- collective implosion accelerator
- acceleration by electron plasma wave in metal
- laser acceleration along crystal channel
- acceleration by stimulated emission of radiation

The problem is that each concept requires substantial resources and multi-M$ just to do the "proof-of-principle" experiment. The very few proof-of-principle experiments have so far been carefully selected and done at a few beam physics centers. Which ideas, if any, are to flourish is yet to be seen.

Example: One possible path to higher frequencies and higher acceleration gradients (a new frame of beam dynamics will be needed at each step):

accelerator structure	dimension	power source
cylindrical cavities	10 cm	radio-frequency S-band
	⇓	
rectangular cavities	1 mm	radio-frequency W-band
	⇓	
optical fibers	1 μm	optico-frequency laser
	⇓	
crystals	1 Angstrom	X-ray laser

Other research Topics

Radiation effects
  - extremely high brightness (short bunches and small emittances)
  - electron-photon interaction
  - high order QED
  - free electron lasers
  - laser cooling
  - lowest quantum state cooling
  - X-ray free electron lasers
  - extremely high energy densities

Plasma lens
Origin of high energy cosmic rays
Micro-machining
High power computing
Digital electronics
High temperature superconducting devices
Spin dynamics
Crystalline beams
Advanced Instrumentation

etc…

Summary remark

Lots of challenges and interesting research topics. I have at best conveyed a glimpse. And I think it should be taught in the universities.