Accelerators

R. B. Palmer

BNL 60th Birthday

- Introduction
- Early History
- Strong Focusing
- Colliders
- The Energy Frontier

INTRODUCTION

Acceleration

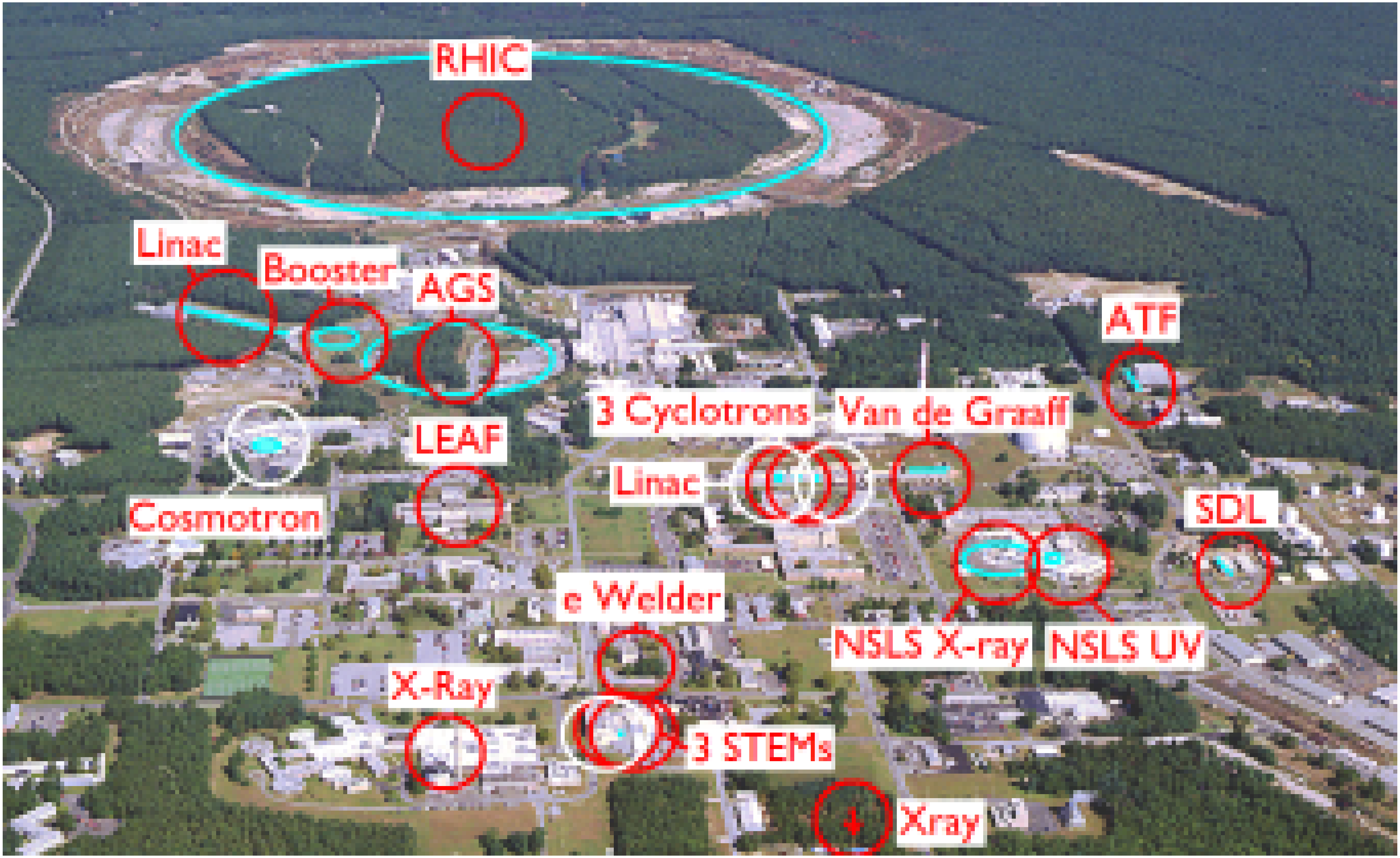
- Acceleration is making things go faster
- But if you push hard enough, things approach the velocity of light and cannot go much faster
- So we talk not of their speed, but of their ENERGY
- Which we measure by the volts it would need to give an electron (or proton) that energy: ELECTRON VOLTS

approx 1 Volt 2 inches

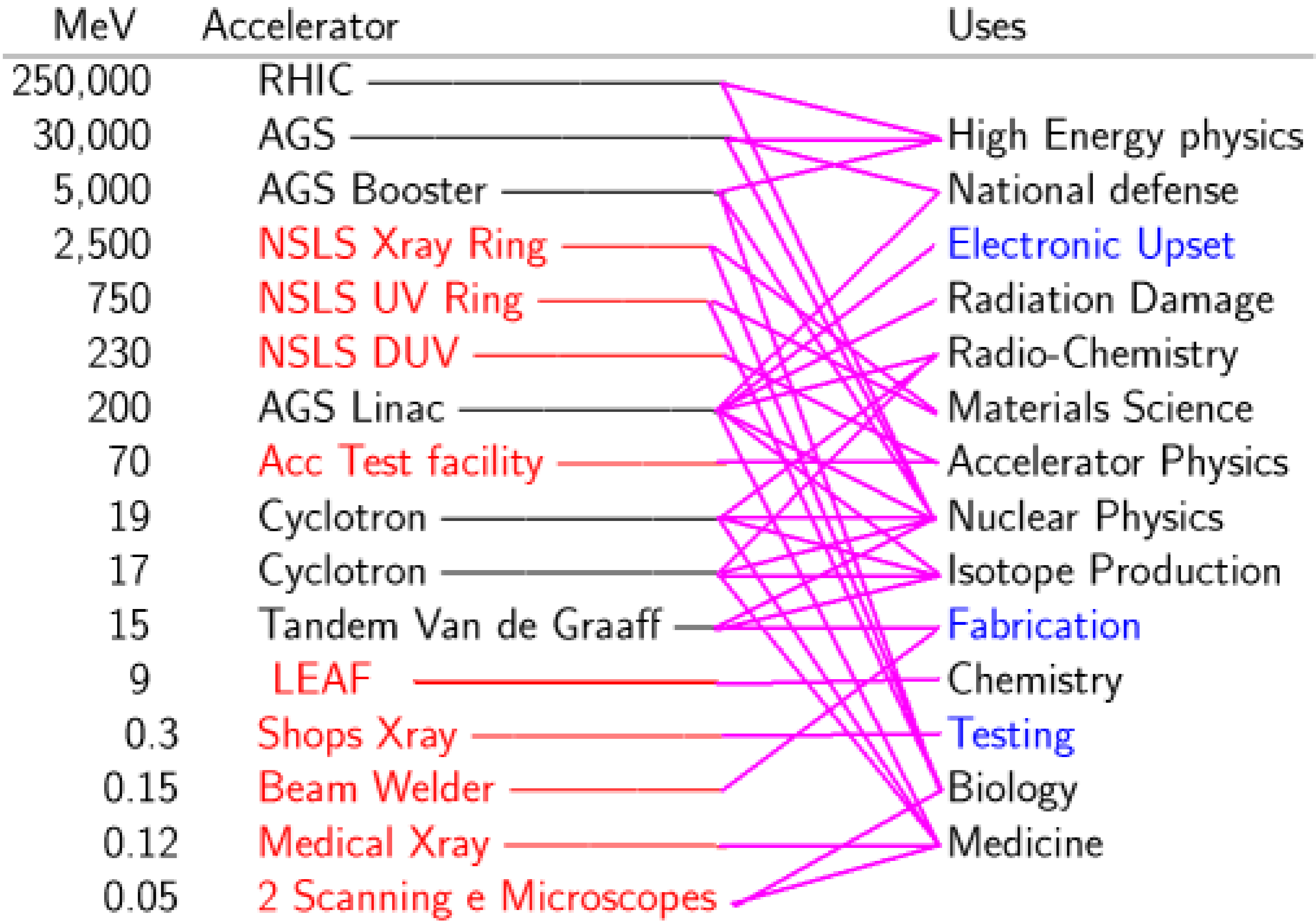
1000 eV = 1 keV
1000,000 eV = 1 MeV
1000,000,000 eV = 1 GeV
1000,000,000,000 eV = 1 TeV

For 1 TeV: 30 million miles of batteries on end

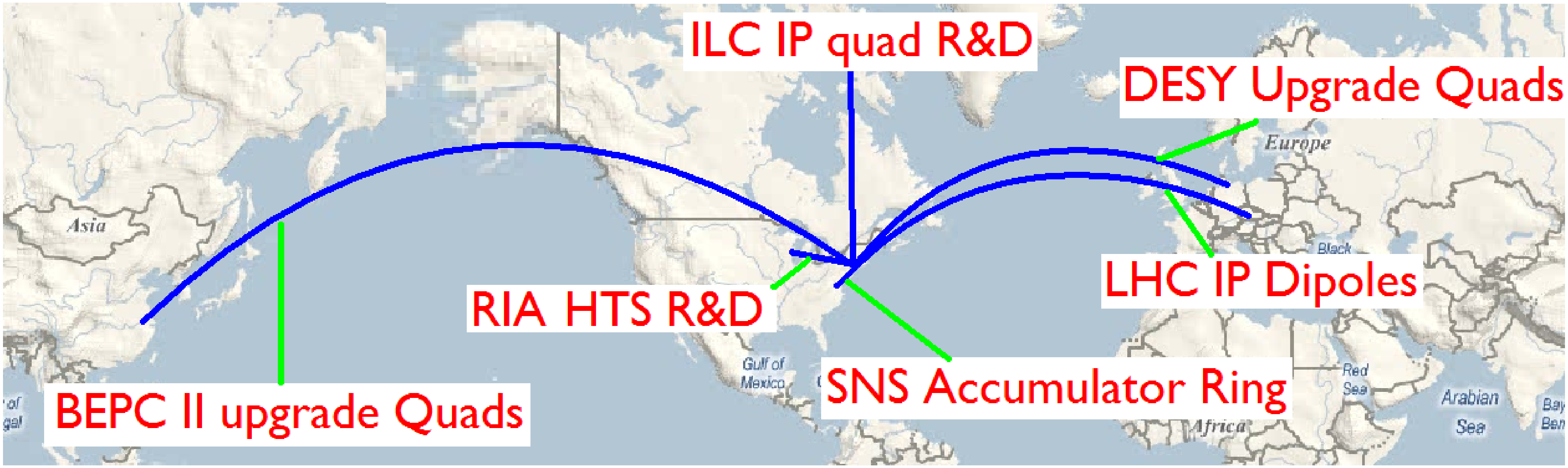
Accelerators are everywhere at BNL



And they do everything

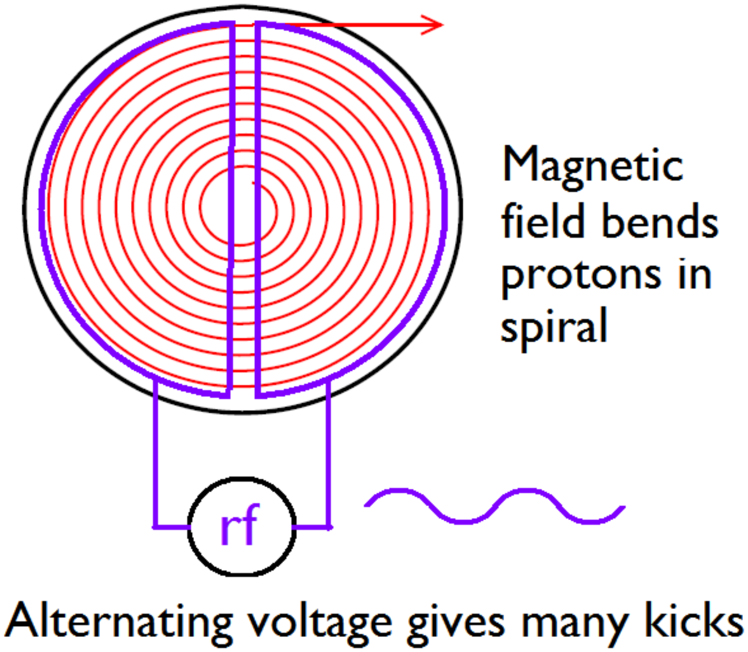


BNL made equipment and R&D for many others



EARLY HISTORY

1930-1932 in Berkeley The First Cyclotrons



Lawrence

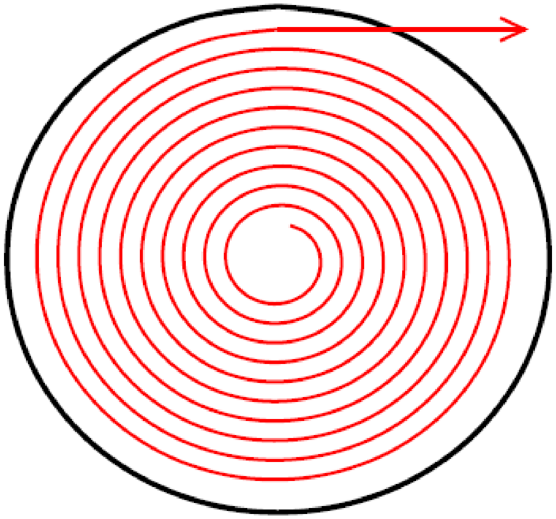
Livingston

1931 4" Cyclotron (with no focusing) 80 keV
1932 11" Cyclotron (with magnetic focusing) 1.22 MeV

"Lawrence was my teacher when I built the first cyclotron
He got the Nobel Prize for it - I got a PhD"

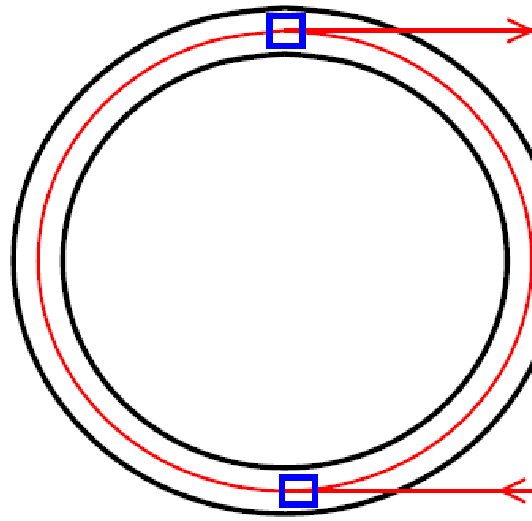
But it was Lawrence's idea

1945 Cyclotron → Synchrotron



Cyclotron

Fixed Field



Synchrotron

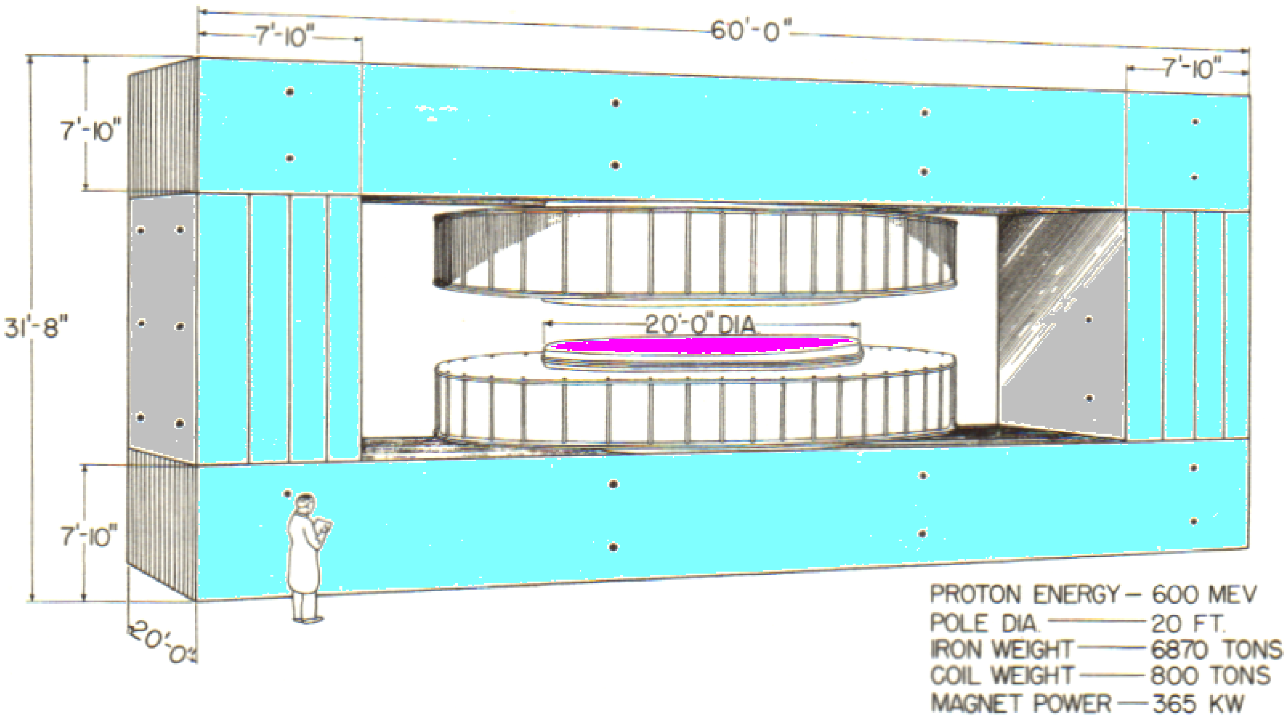
Field ramped

Oliphant

Marcus Oliphant, an Australian, invented the synchrotron while in Berkeley in 1945 and proposed it to the UK Atomic Energy Directorate after the war.

In 1953 his machine, (just less than 1 GeV) finally ran, but it was not the first. By then the BNL Cosmotron had been running for over a year.

1946 Brookhaven Plans



Rabi

Livingston was to lead the BNL Accelerator effort: a Van-de-Graaff, a 60" cyclotron, and something bigger.

Livingston wanted to build a 240 inch Cyclotron. Rabi, a trustee, wanted a higher energy Synchrotron. Livingston said it might not work. Rabi said "go for it". Livingston left. BNL build a Synchrotron.

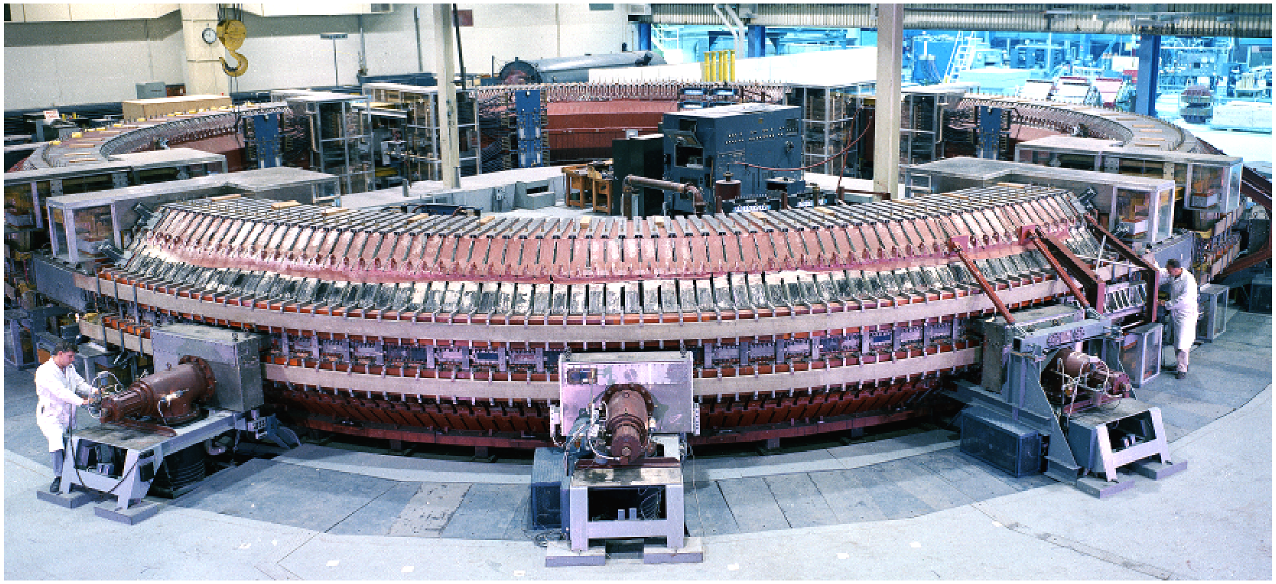
Cosmotron

The AEC supported two synchrotrons: 3 GeV at BNL and 6 GEV at Berkeley. Berkeley decided to build a 1/4 model first.

BNL went straight ahead, choosing a 25" x 6" beam aperture.

Then the Berkeley model indicated that this was too small, and they picked 168" x 48". It was too late for BNL to change.

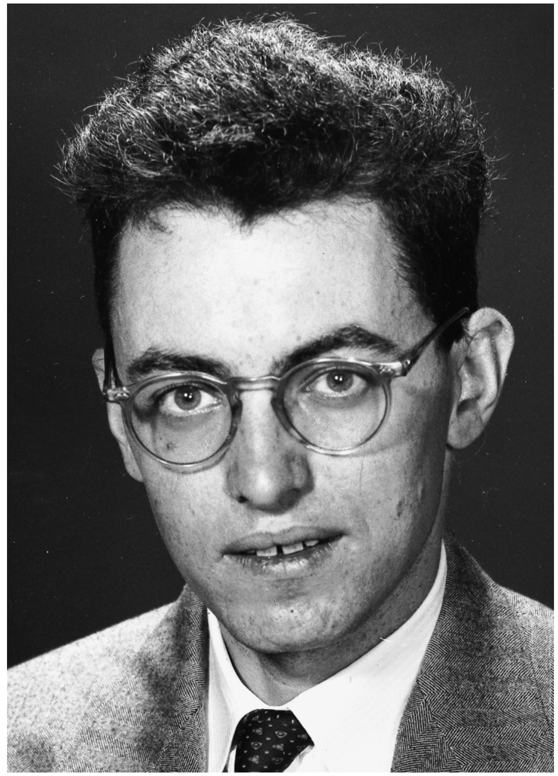
But the Cosmotron worked just fine! It ran first in 1953 even before Oliphant's. Berkeley was amazed and revised their aperture down from the 168" x 48" Jeepatron to 48" x 12".



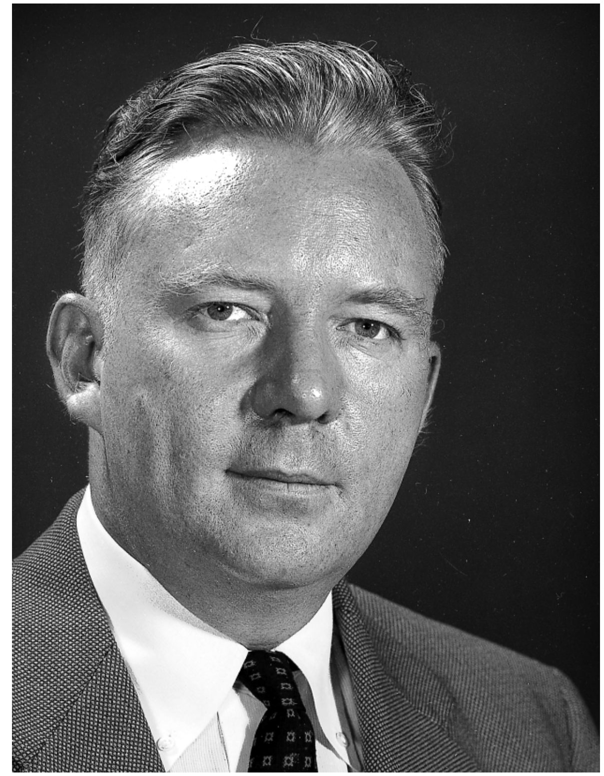
STRONG FOCUSING

The 1952 Revolution

In Europe, CERN was established and, before the Cosmotron had run, their accelerator experts came to BNL to learn how to build such a machine.



Courant

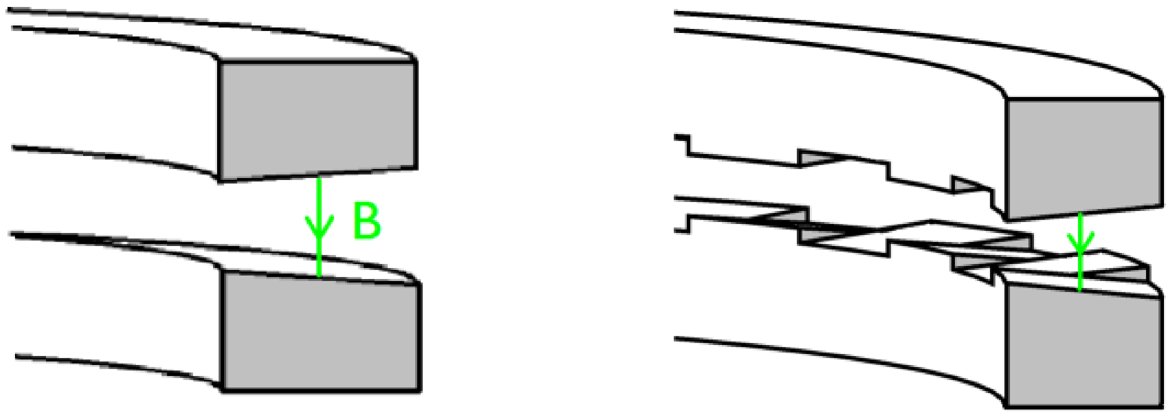


Snyder

Livingston, visiting BNL from MIT, wondered if the Cosmotron could be improved if some of the C magnets were reversed, but feared that the resulting alternation of gradients would hurt.

Courant and Snyder discovered that it helped a lot ! "Strong Focusing" was invented, together with a whole new mathematical toolkit.

Strong Focusing



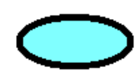
Old Style
"Weak" Focus

Alternating Gradient Synchrotron
Strong Focus

Strong focusing allows much smaller beam dimensions, and thus smaller magnets. For the cost of a 10 GeV weak focus machine, one could build a 25 GeV one.

Beam Pipe sizes

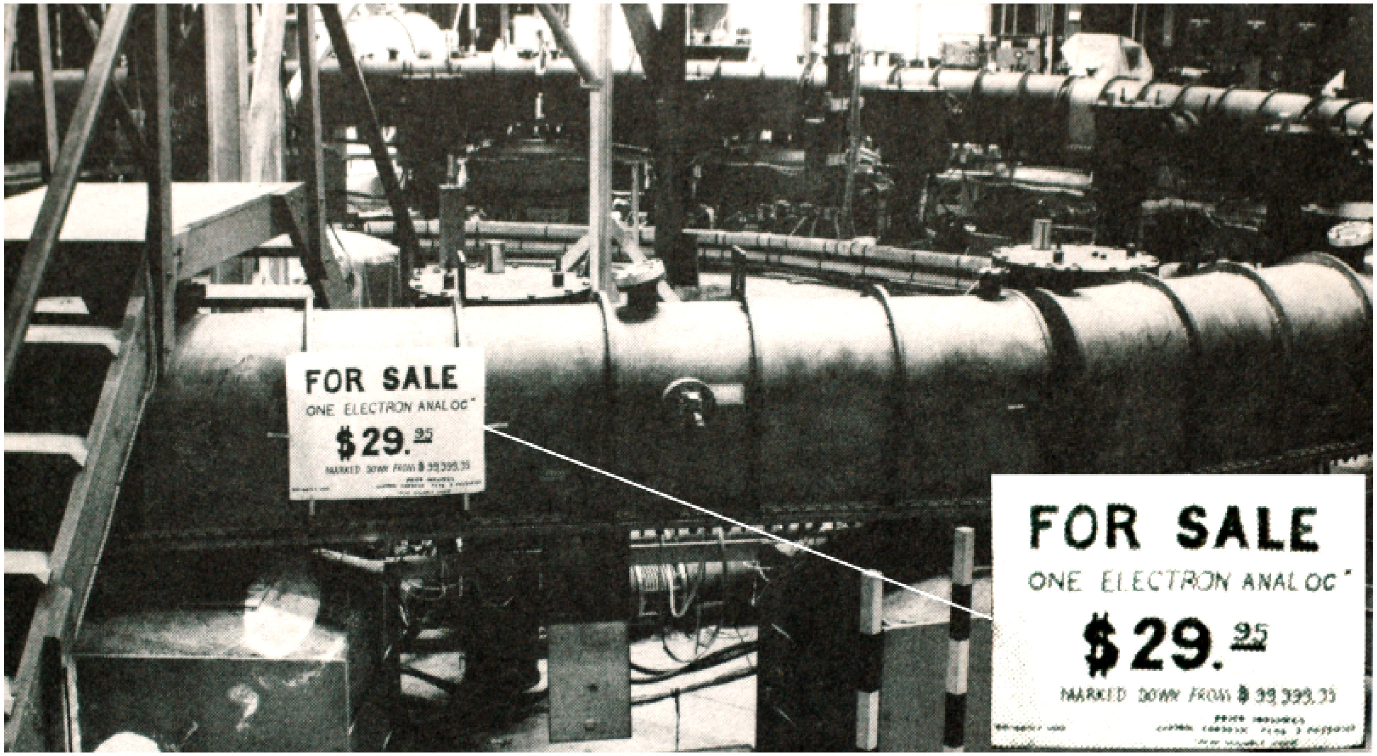
Weak Focus
Cosmotron



Strong Focus
AGS

Electron Analog

With Strong focusing, particles accelerate through an unstable 'transition'. Fearing that this might not work, BNL decided to build an 'Electron Analog'.



CERN, with greater courage, decided to go ahead at once with their PS, and thus beat BNL. The Analog worked fine, though transition remains a source for losses in all machines that have it.

Cornell, with a strong focus electron machine got there even before CERN.

Christofilos

In fact, Christofilos, a Greek elevator operator and self taught scientist had invented strong focusing almost 2 years earlier. His paper, sent to Berkeley, had been assumed crazy.

On a visit to the US, in the Brooklyn library, he chanced to read Courant-Livingston-Snyder's paper and called BNL. He was invited to visit. When they realized the truth, he was hired on the spot.

At Livermore, he later invented Induction Linacs and the Astron plasma confinement.

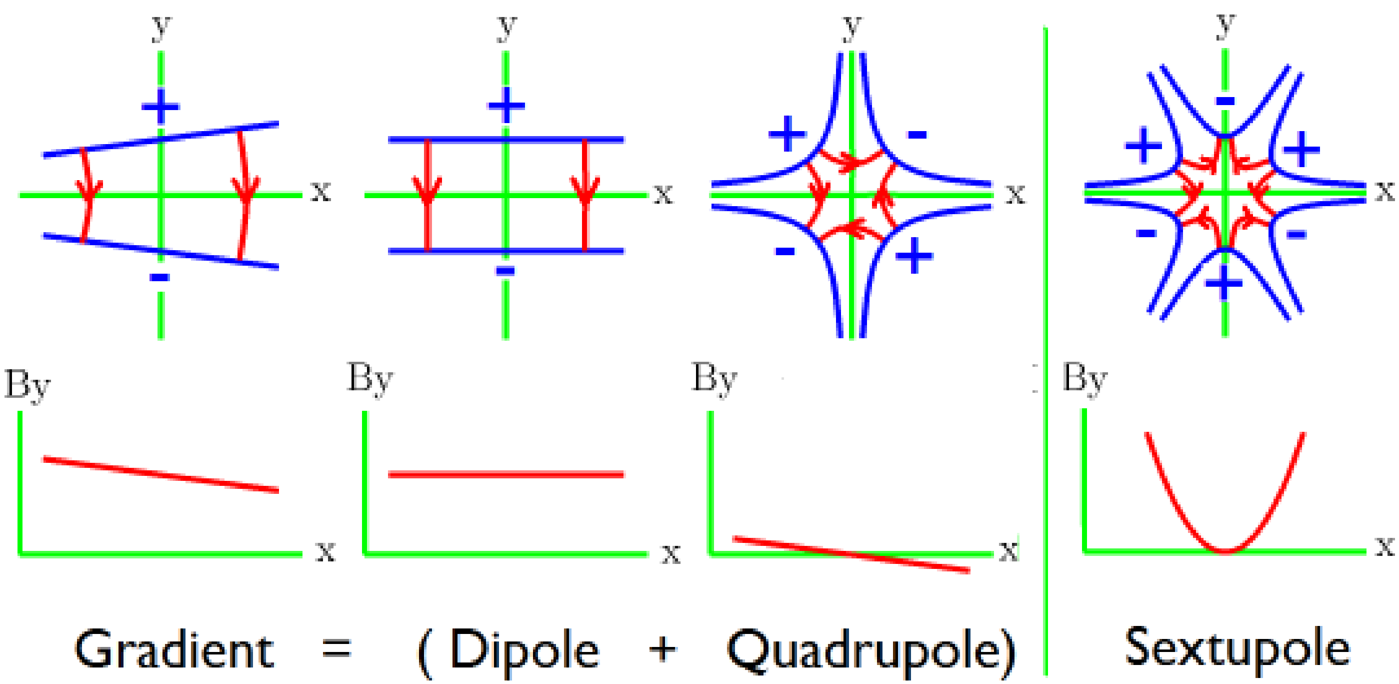
1960 The Alternating Gradient Synchrotron (AGS)

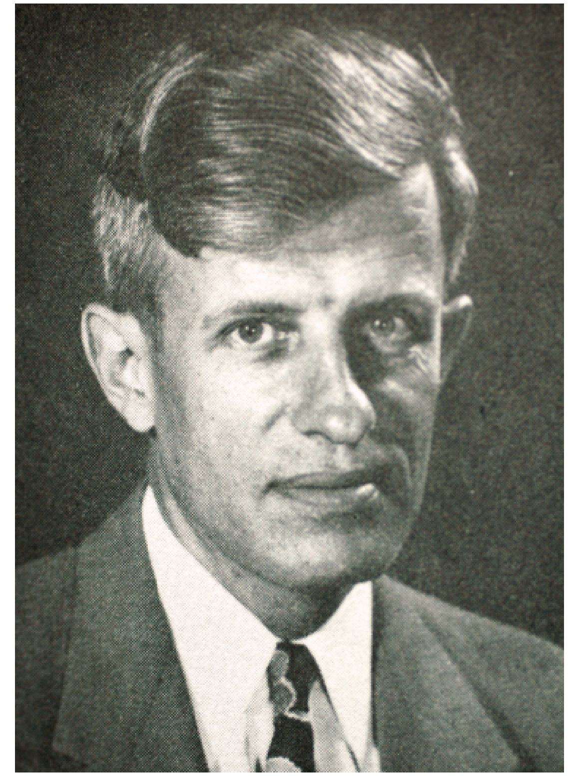
In 1960, just a year after the CERN Proton synchrotron (PS), the AGS started operation. As you will hear, it has been one of the most productive "Engines of Discovery" ever built, and it is still running as an injector into RHIC.

Lattices

Courant and Snyder's discoveries and theory led to a whole new art/science of lattice design

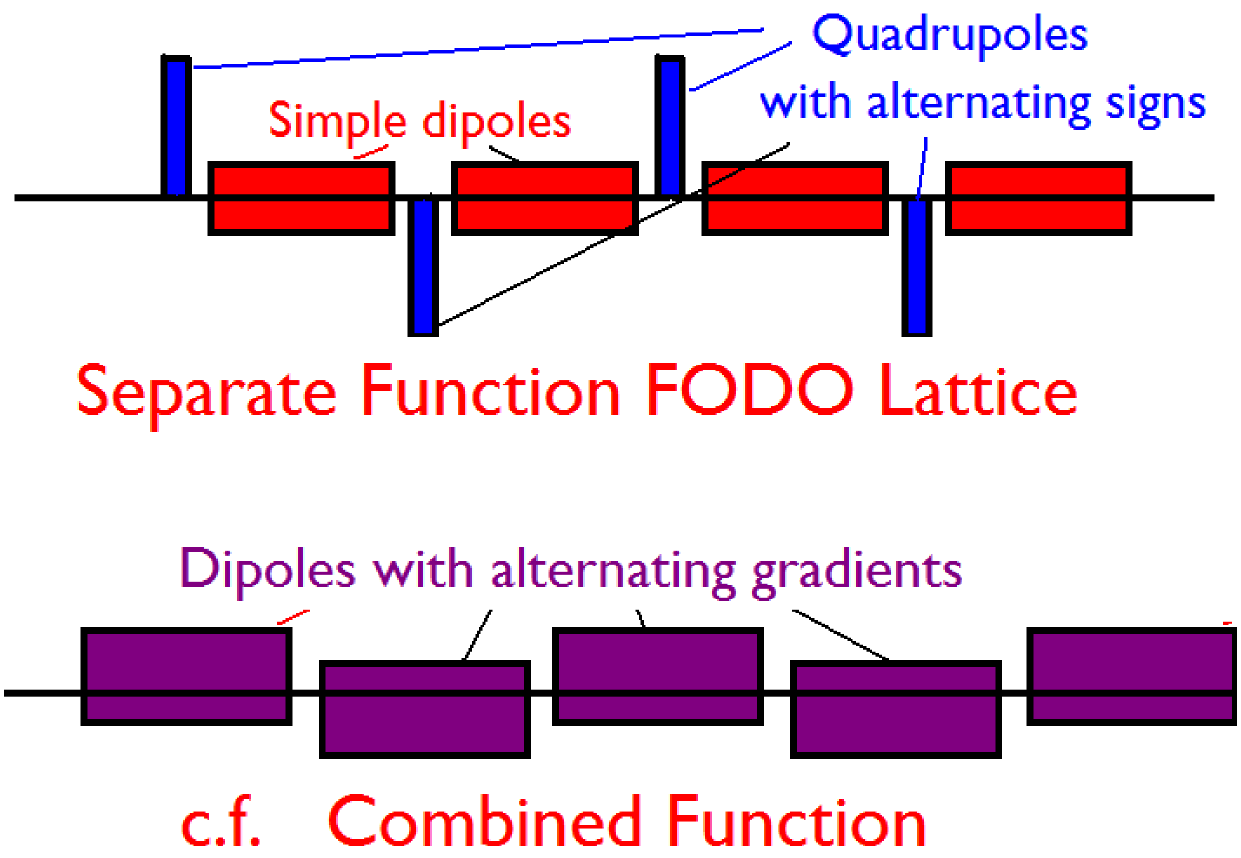
- Blewett proposed linear accelerators focused by alternating quads (without dipoles).
- With sextupoles, came "chromatic correction"
- More specialized lattices were invented (next)

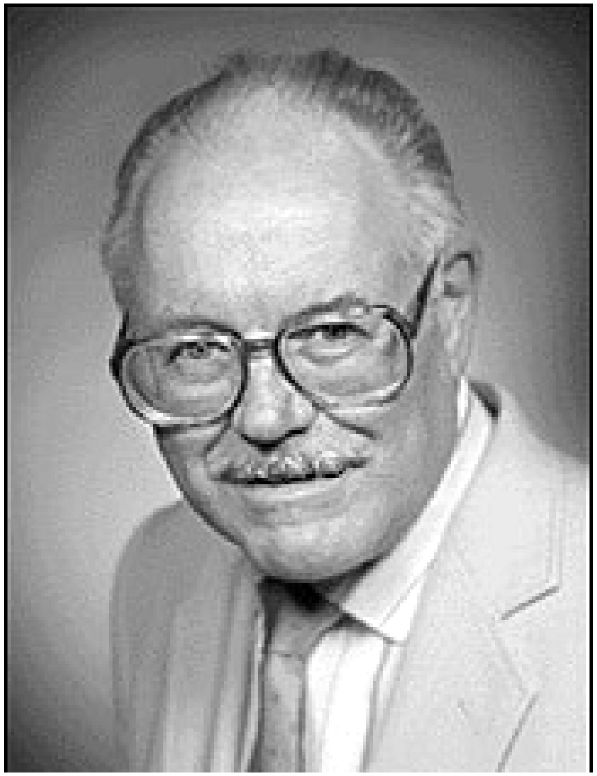




Blewett

1) FODO: Separated Function Lattice





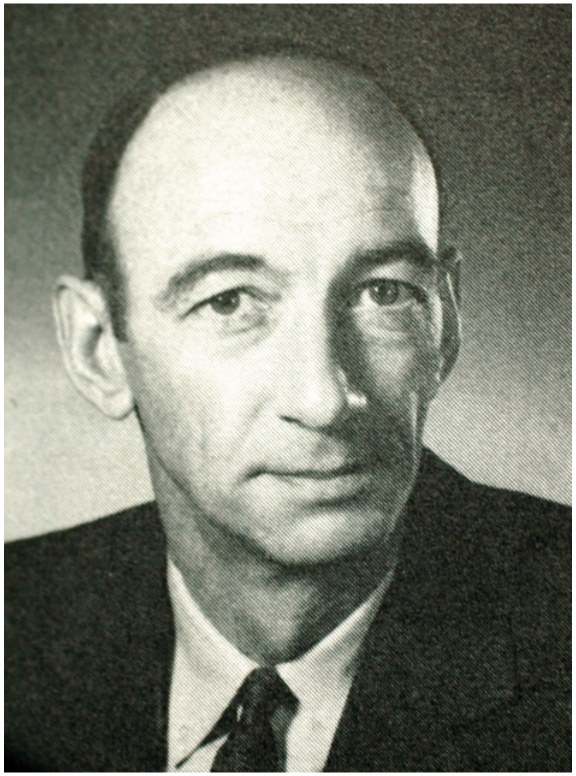
Danby

Allows separate control of bending and focus. This, with the addition of sextupoles, is now the 'standard' bending lattice; first used by Wilson at FNAL.

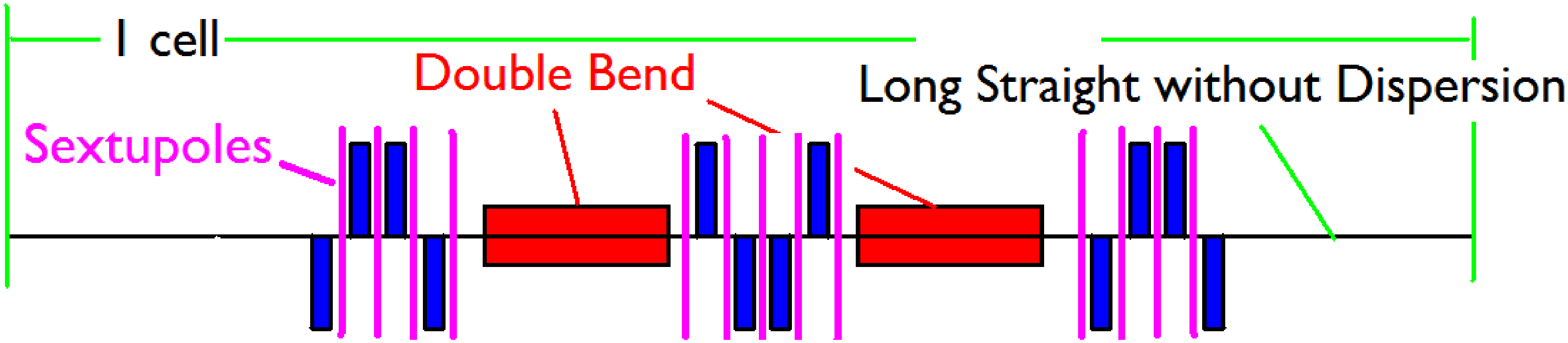
2) Chasman Green

Used in Light sources: the Double Bend Achromat is designed to give small quantum fluctuations and provide dispersion free "straights" for other equipment (NSLS NSLS II, ESRF Grenoble, APS Argonne, Spring-8 Japan)

Chasman

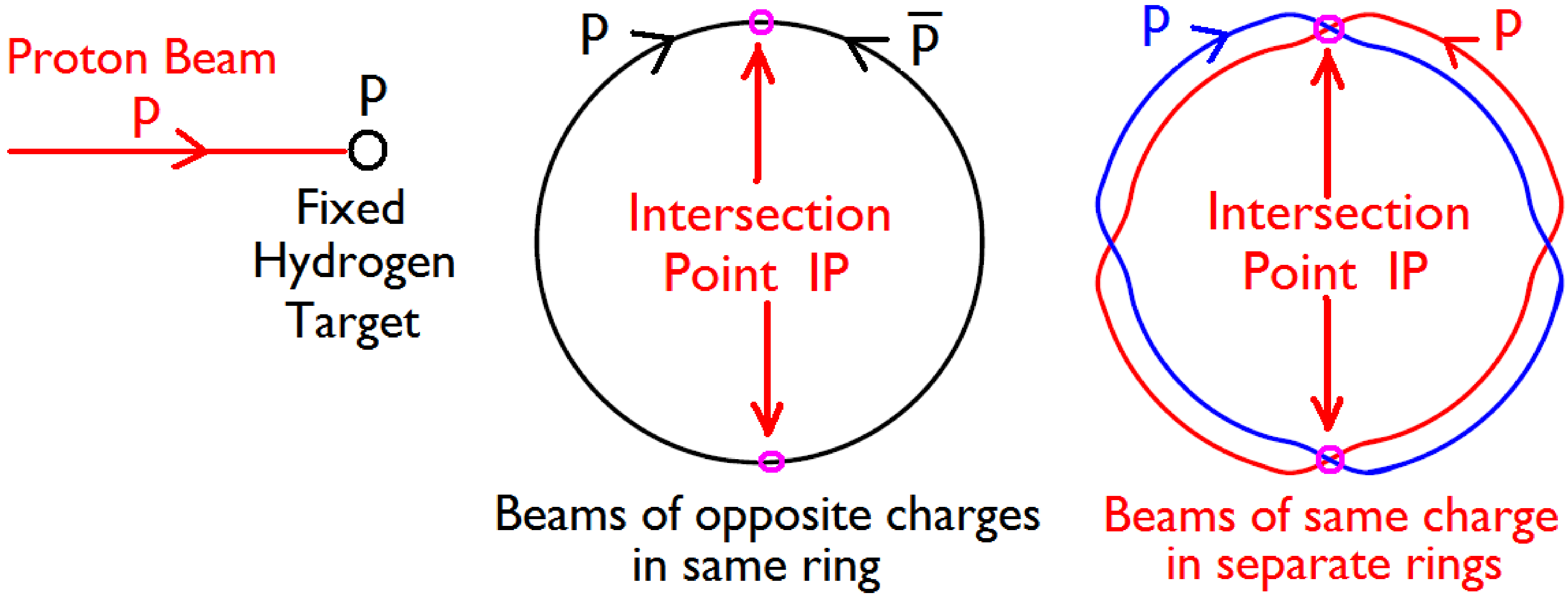


Green



COLLIDERS

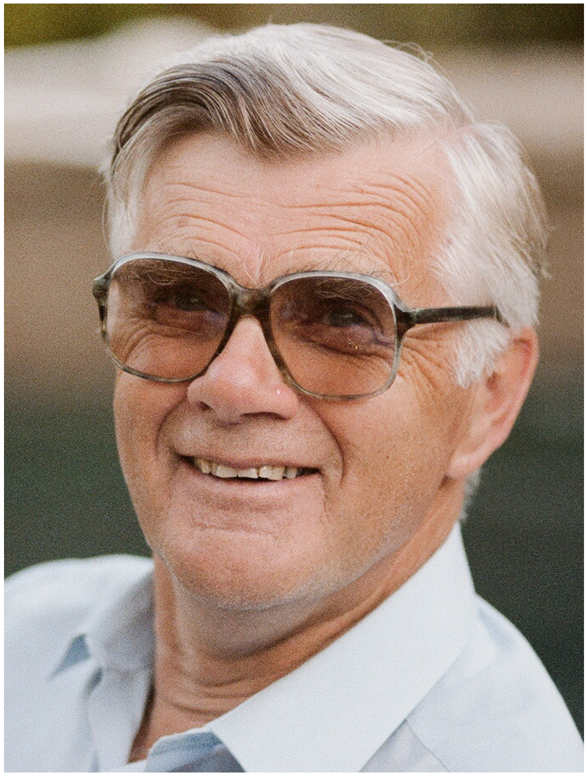
Collider types



- From relativity this gives huge gains in effective energy
- Single proton-antiproton ring is cheaper and may already exist
- But making enough antiprotons is harder giving lower luminosity

1969 First p-p (Two Ring) Collider: 30 GeV ISR

ISR at CERN, Switzerland



Johnsen
Later at BNL

The ISR, built with incredible care, worked incredibly well.

Leading, later, to the decision for BNL to build a 400 GeV ISA to be called "Isabelle", but the invention of $\bar{p} - p$ gave competition.

1994 The 1st p-$\bar{p}$ Collider: 400 GeV SPPS

CERN, Switzerland

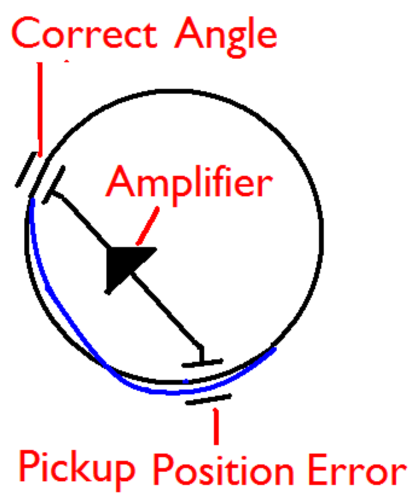
The problem is making and "cooling" the anti-protons ($\bar{p}$'s).

Van der Meer invented Stochastic Cooling in transverse directions.

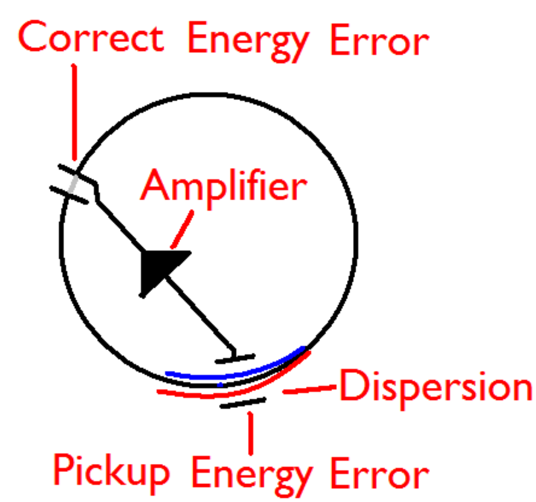
In a workshop at BNL, I suggested the extension to cooling momentum, and was surprised to find myself acknowledged!

Rubbia

Van der Meer



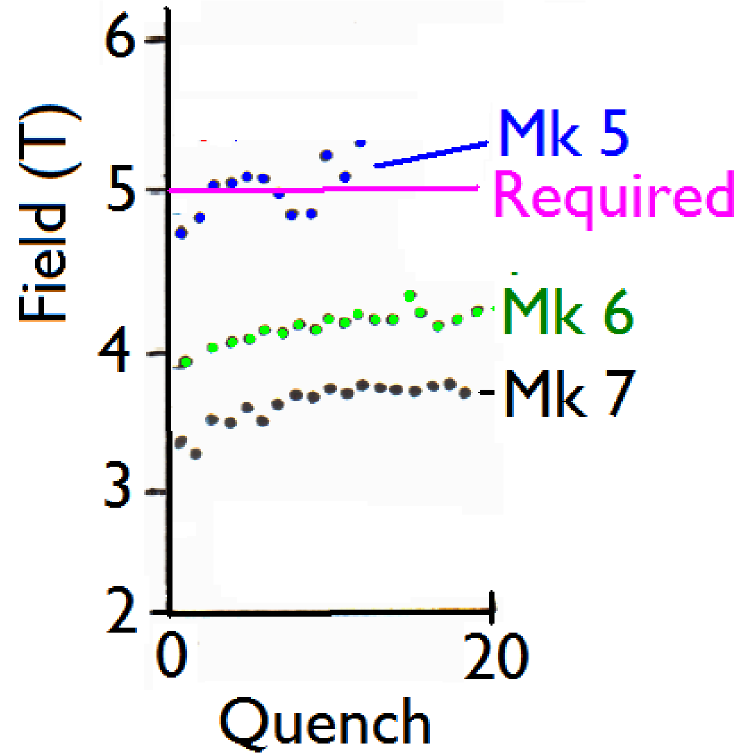
Van der Meer



Palmer

Isabelle at BNL

FNAL was working on magnets for a superconducting 1 TeV "Energy Saver/Doubler", that could now become a 1 TeV $\bar{p} - p$ collider. BNL was working on the lower energy 400 GeV, but higher luminosity, p-p Isabelle.



After some initial magnet success at BNL, production was then handed off to Grumman. By the 5th industrial magnet, the desired field was reached.

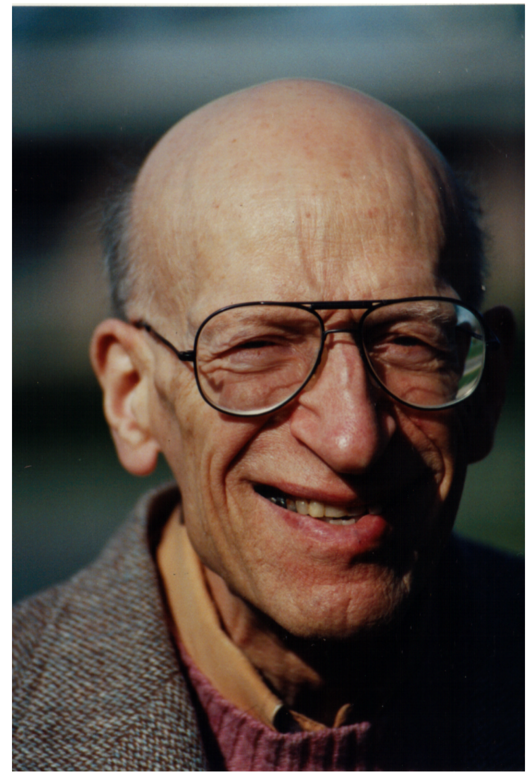
But the 6th did not do so well and the 7th did worse.

A small group in Physics believed we had the answer, but lab management did not support us. Samios (Physics chairman) could provide only 30 k$, about 1/10th of what was needed, but we started anyway.

Palmer Magnet

Goodzeit

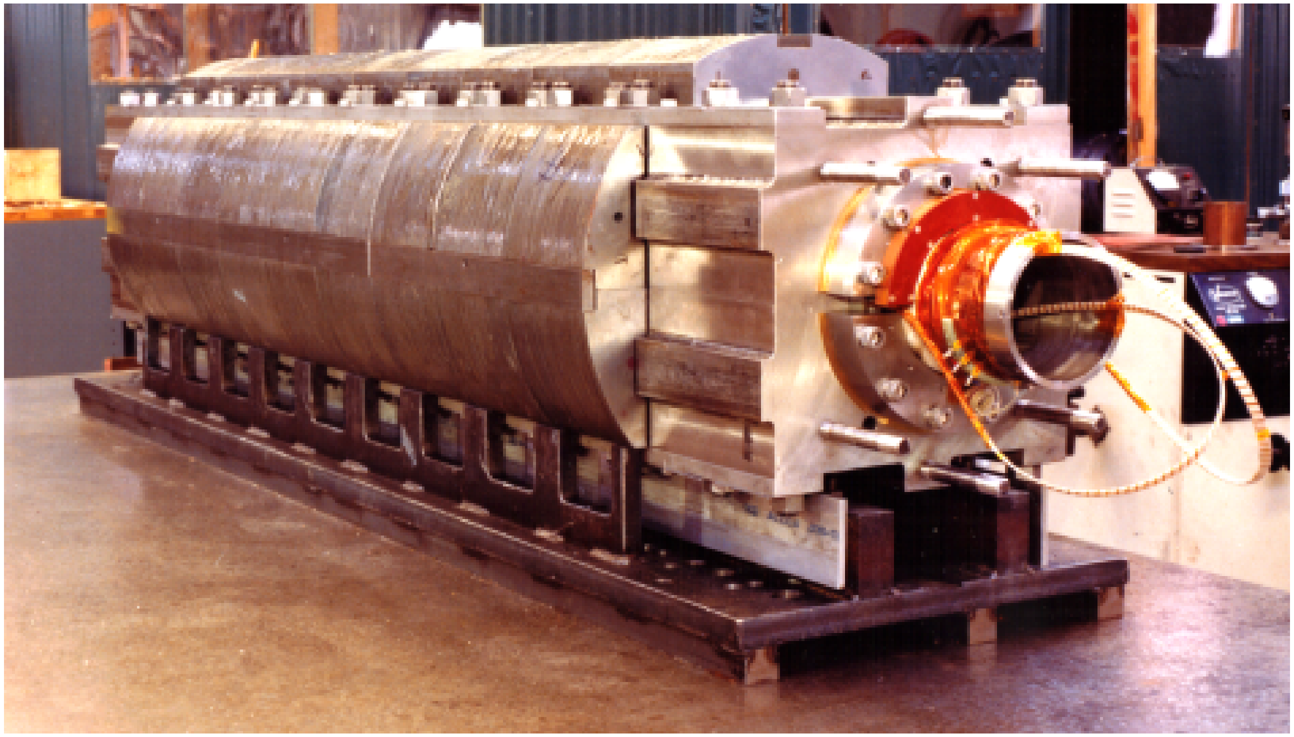
Samios

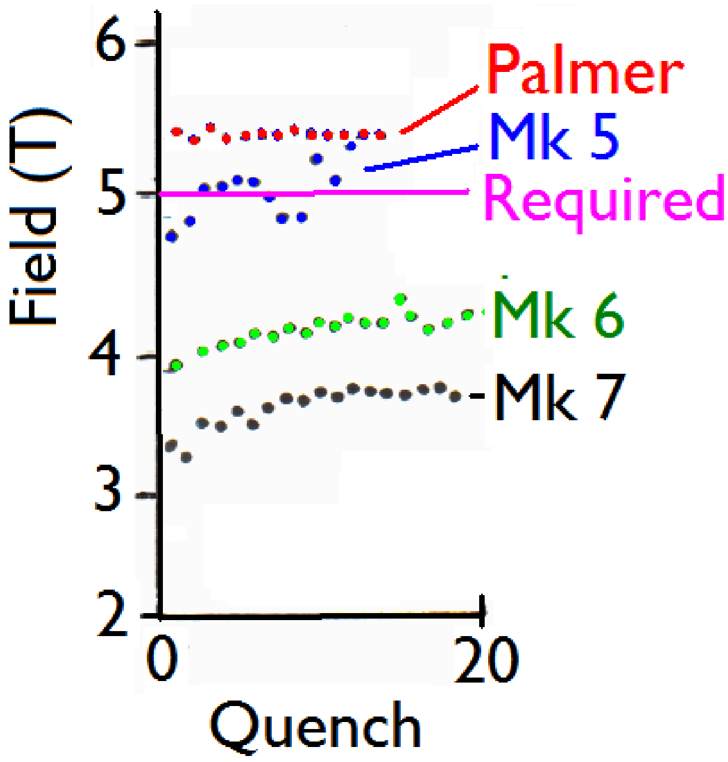


Shutt

Without official priority in the BNL shops, we machined our parts mostly at the MIT Magnet Lab (thanks to Marsden). And when we needed it, we discovered a secret priority with BNL shop's Bob Lehn. Marsden, conveniently, did not send BNL the bills till after the magnet was complete. The total was nearly 300 k$!

6 Months later our prototype worked perfectly



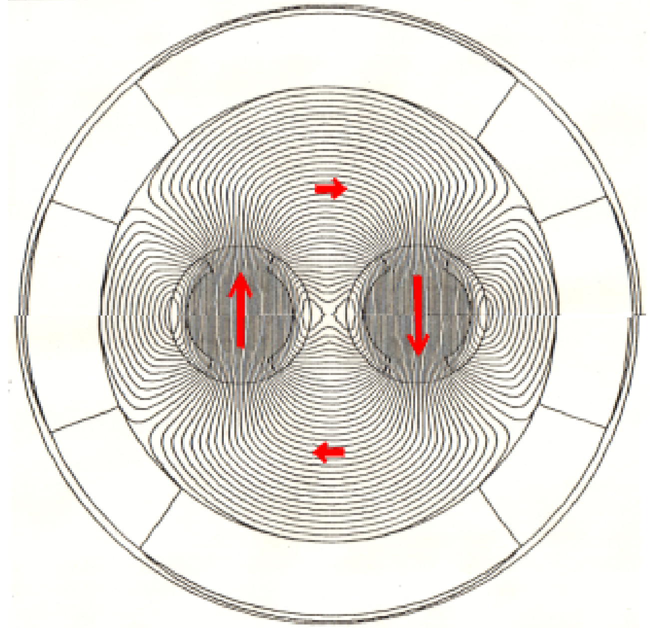


- Samios became the Lab Director
- Nobody worried about the 300 k$

But it was too late. Isabelle was canceled, but we got RHIC, and the BNL magnet concepts became standard:

Cold Iron | Spacers for field quality | Pre-compression

Another idea not lost: 2 in 1

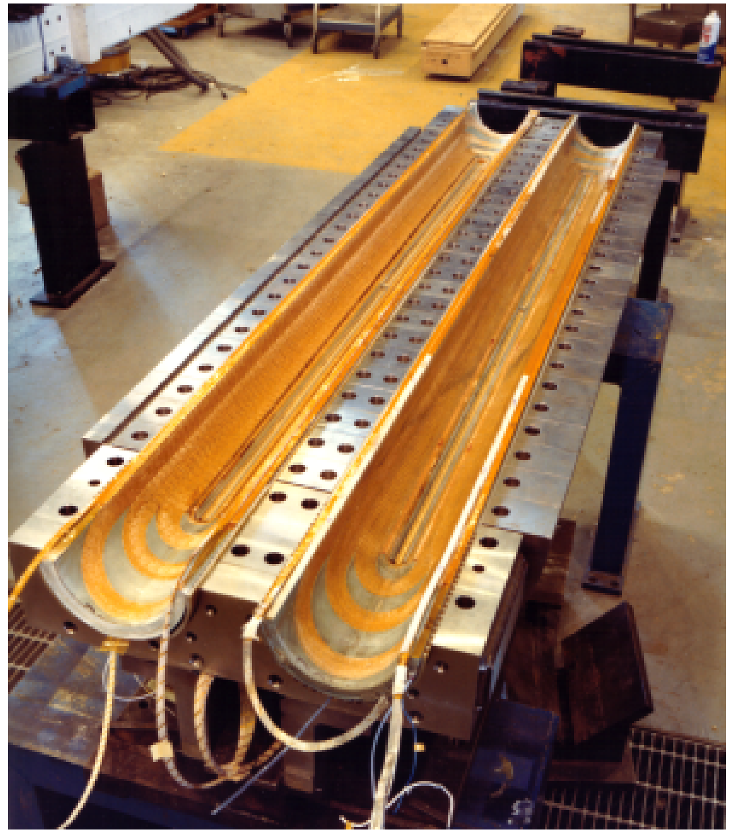


- Mount 2 dipoles in one Fe yoke
- Uses less Fe
- And less SC
- Lower cost

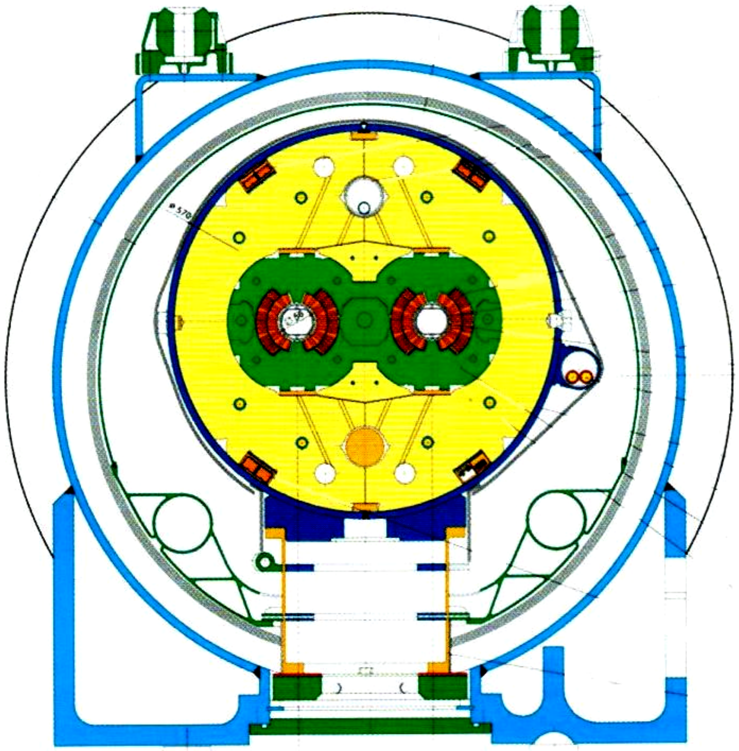
- Built prototypes for Isabelle
- Isabelle rejected them

- Built prototypes for SSC
- SSC rejected them

- But the LHC chose them
  If LHC fails, you know who to blame



CERN Switzerland 7 TeV Large Hadron Collider (LHC)



Due to operate next year, it will be the world's highest energy machine. The US, including BNL, played significant roles in its construction, supplying special magnets for its intersection regions, and supporting startup and R&D for future upgrades.

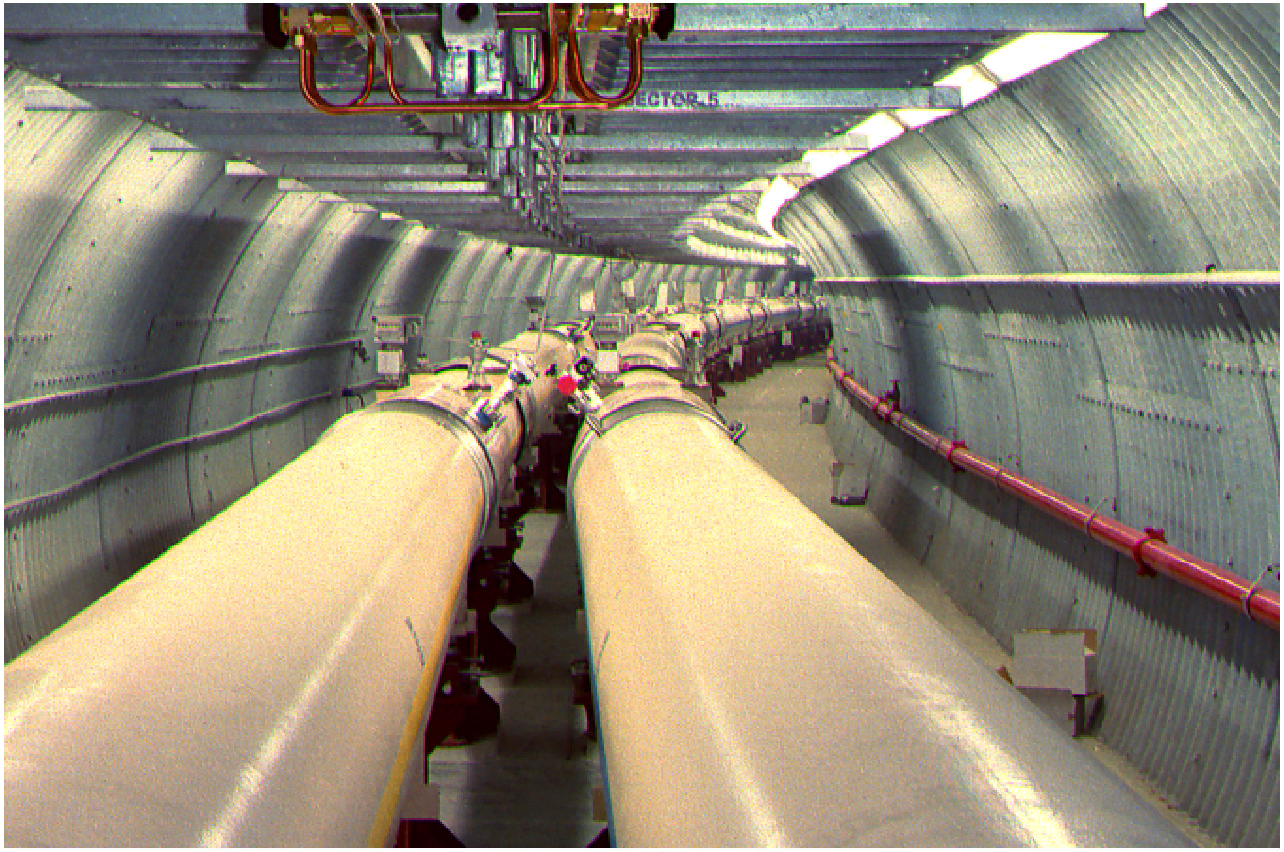
In the mean time BNL got the

250 GeV Relativistic Heavy Ion Collider (RHIC)

- Used Isabelle tunnel
- Isabelle refrigerator
- Isabelle magnet ideas
- But was not Isabelle

And RHIC, studying Heavy-Ion Heavy-Ion collisions, has proved far more exciting than Isabelle would have been.

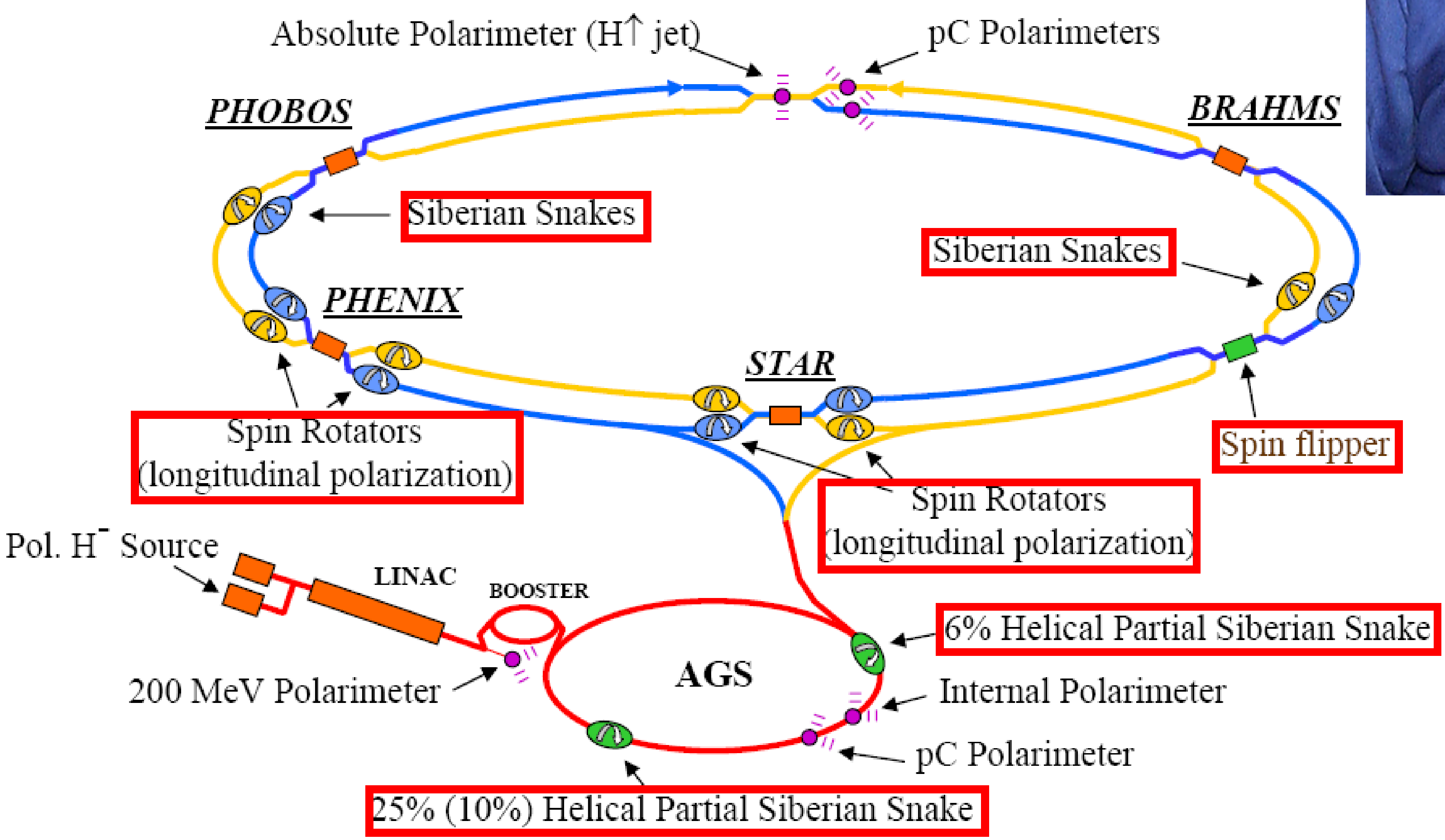
Ozaki



Spin in RHIC

RHIC has continued the planned Isabelle study of the spin dependence p-p interactions. To do this required elaborate and subtle spin manipulations to avoid the 1000 or more spin destroying resonances.

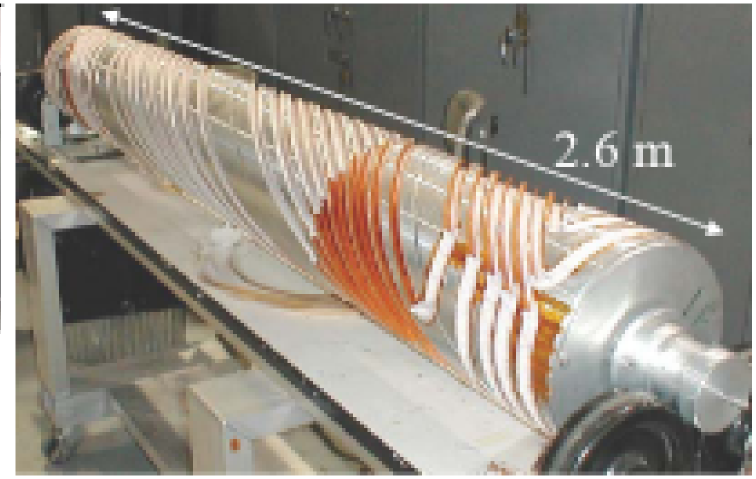
Roser



What are these Siberian Snakes ?

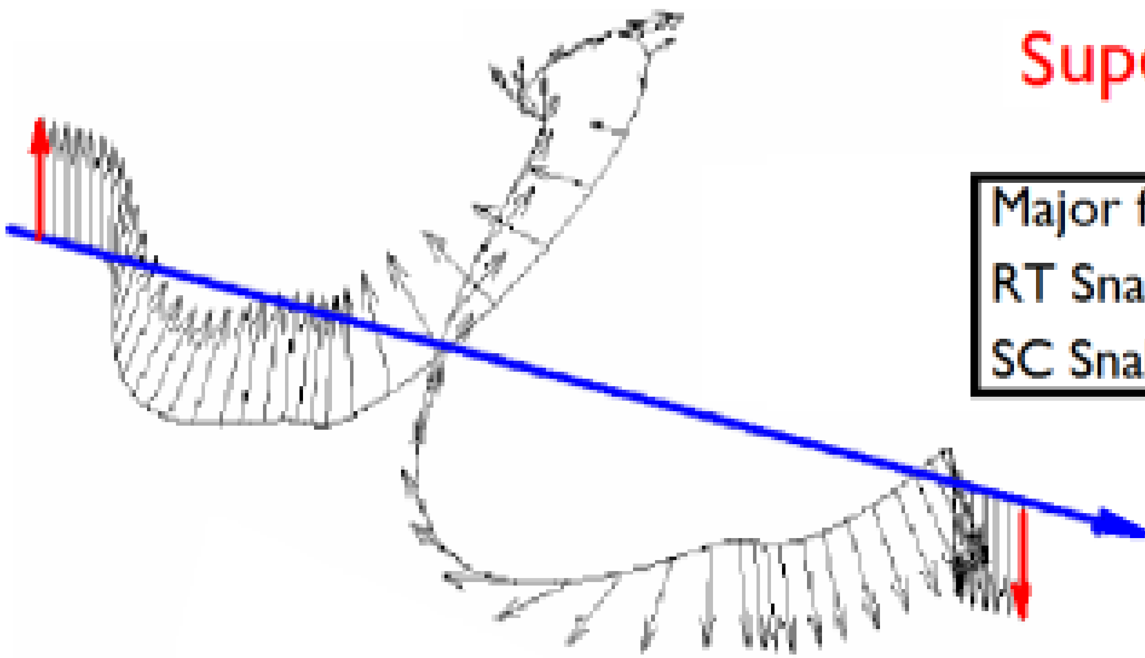
Proposed by Derbenev and Kondratenko in Novosibirsk in 1974

Room Temp Snake



Superconducting Snake

Major finding from RIKEN, Japan
RT Snake from Tokano Ind., Japan
SC Snake from BNL

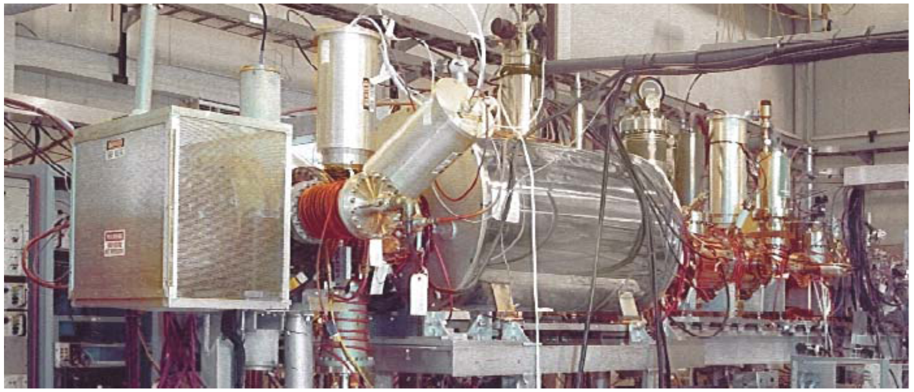


How the spin evolves through a snake

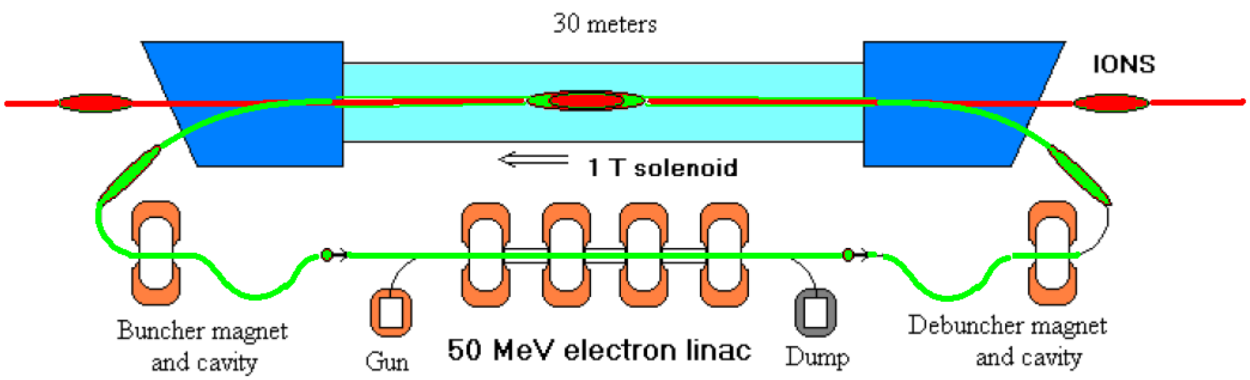
RHIC Upgrade   An ongoing effort to increase luminosity:

- Bunched beam stochastic cooling   A First
  CERN and Fermilab had tried and failed
- Electon Beam Ion Source (EBIS)   Already tested
- Design of the highest energy Electron Beam Cooling
  Using "Energy Recovery Linac"

EBIS

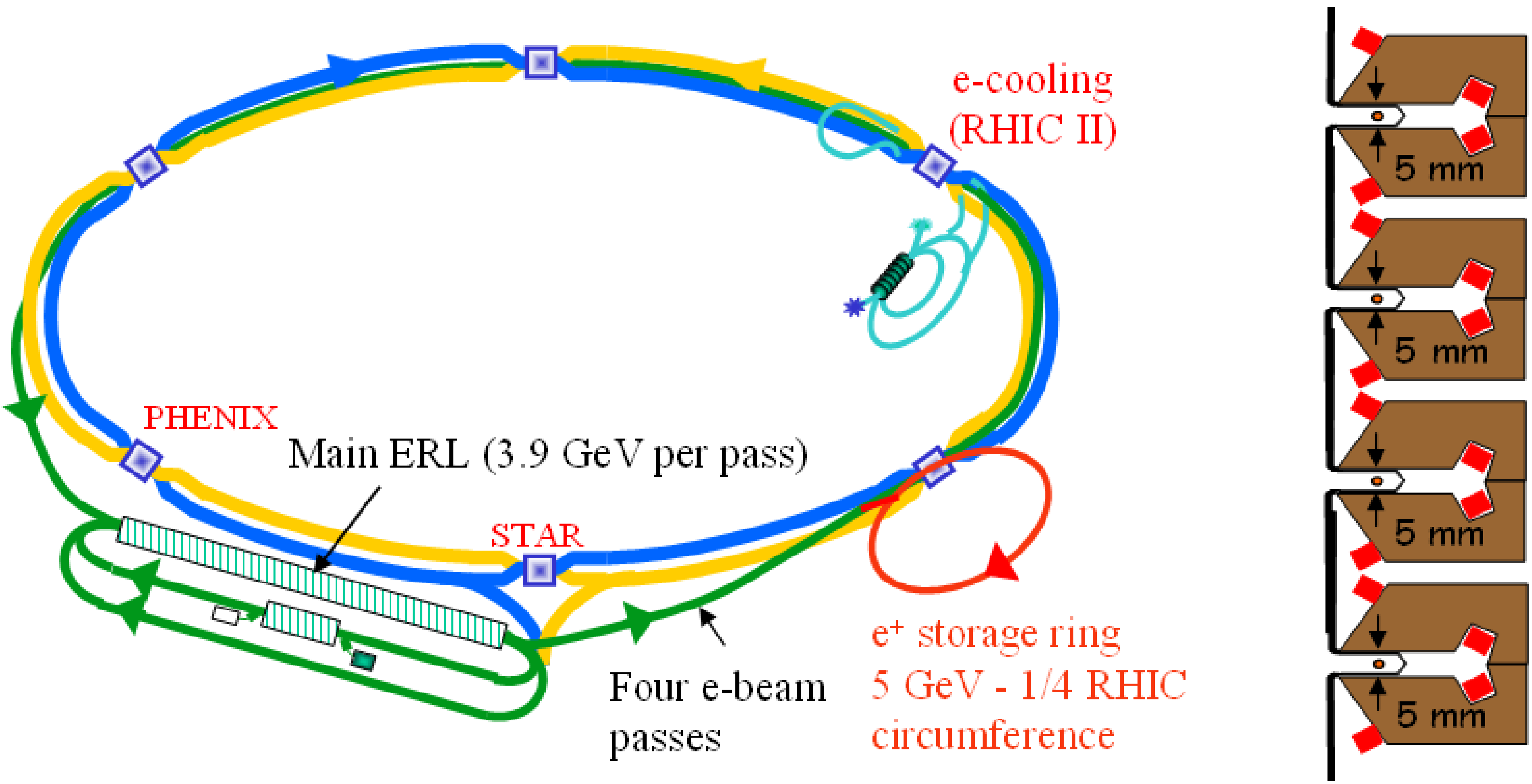


Electron Cooling



BNL Proposed Electron-Heavy Ion Collider: e-RHIC

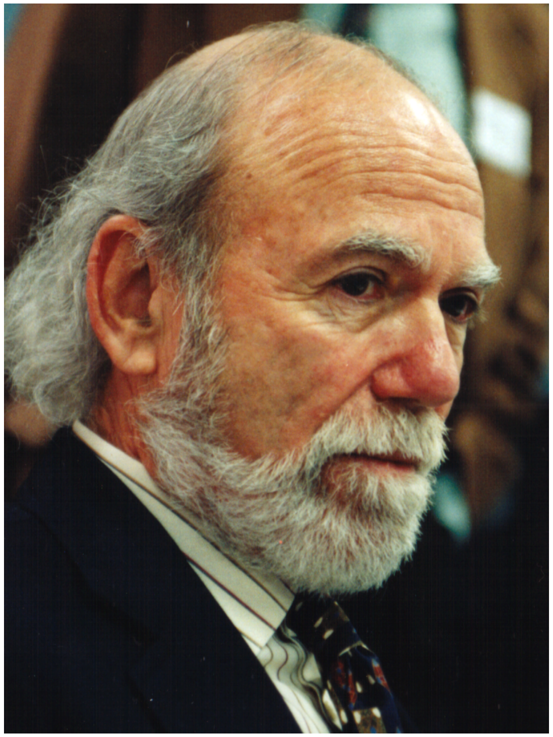
For the future, BNL is proposing to add an electron-Ion capability to RHIC. To get sufficient luminosity a very high electron current is required, again possible using an "Energy Recovery Linac".



Proposed International Linear Collider (ILC)

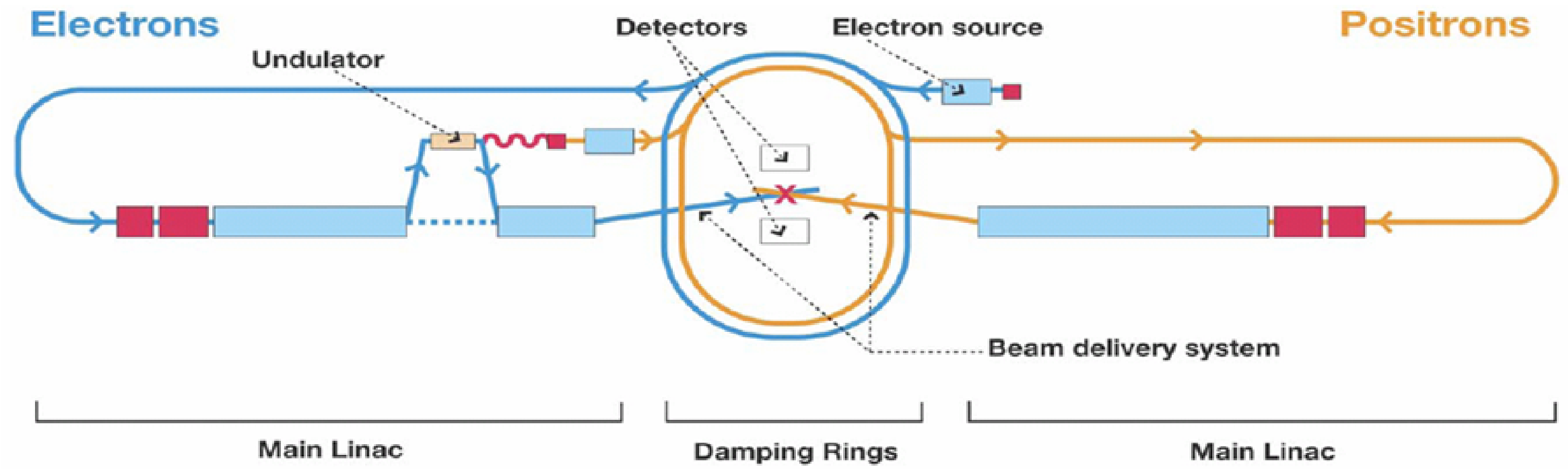
BNL is also contributing to the ILC: an e^+-e^- collider at 250 GeV on 250 GeV.

- Tiny quadrupoles for the final focus
- Scheme for Compton scattered photons for polariazed positron source



Barish

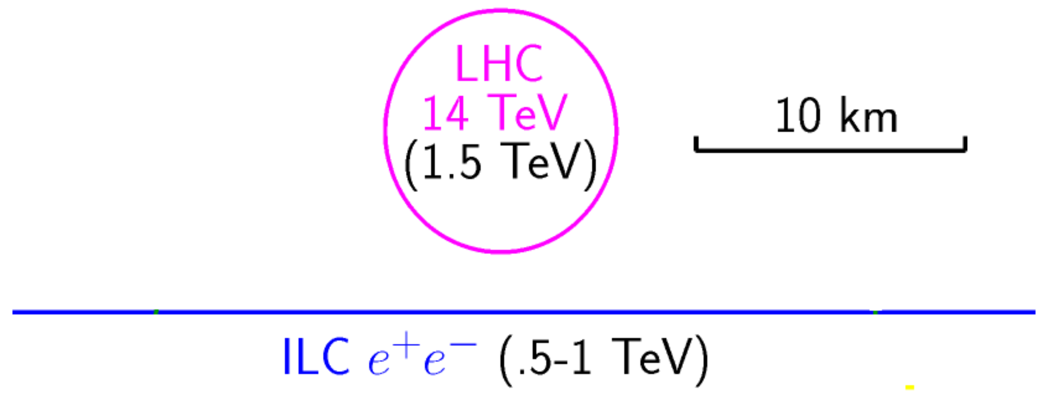
BNL's Harrison



THE ENERGY FRONTIER

The Energy Frontier Problem

- Because a proton is made of many pieces, The useful interaction energy is less ($\approx 1/10$) than that of the whole
- Electrons or muons are points and their full energy counts



- But electron colliders are harder because one cannot bend high energy electrons in circles
- To go to higher energies without getting bigger:
  - Increase bending fields of a proton collider (BNL SC Magnet Group)
  - Increase acceleration rate in an electron linear collider (ATF)
  - Use Muons which, being heavier, do not radiate so much (1/40,000)

BNL Accelerator Test Facility

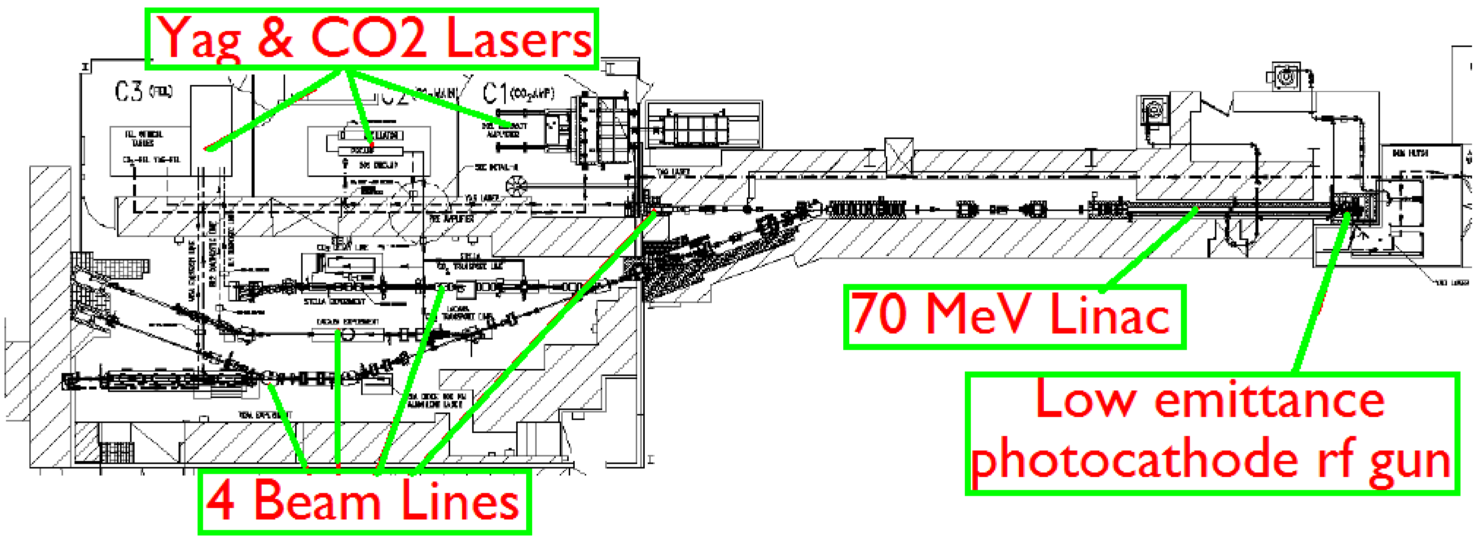
Claudio Pellegrini and I founded the only true user facility devoted solely to accelerator physics.

- Acceleration (10)
  e.g. 2 stage laser acceleration
- Diagnostics(11)
  e.g. Femto sec beam detector
- FEL and other light sources (10)
  e.g. Harmonic FEL → SDL

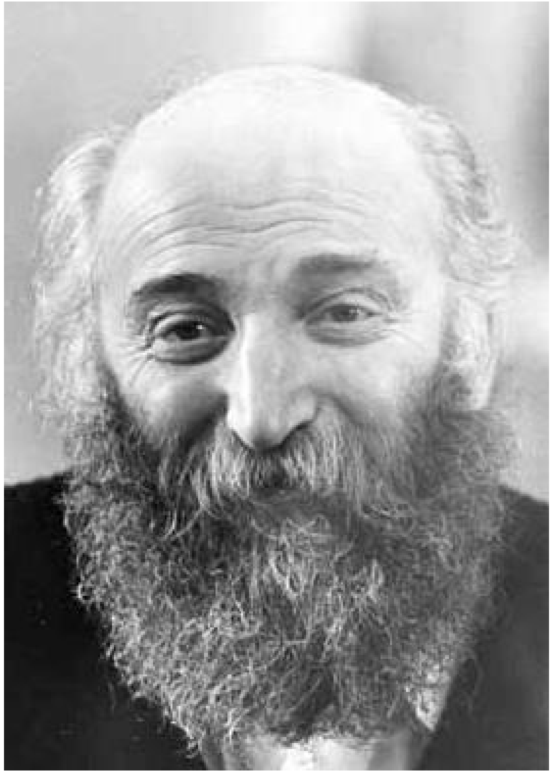
Yakimenko

Pellegrini

Ben-Zvi



Muon Colliders



Budker

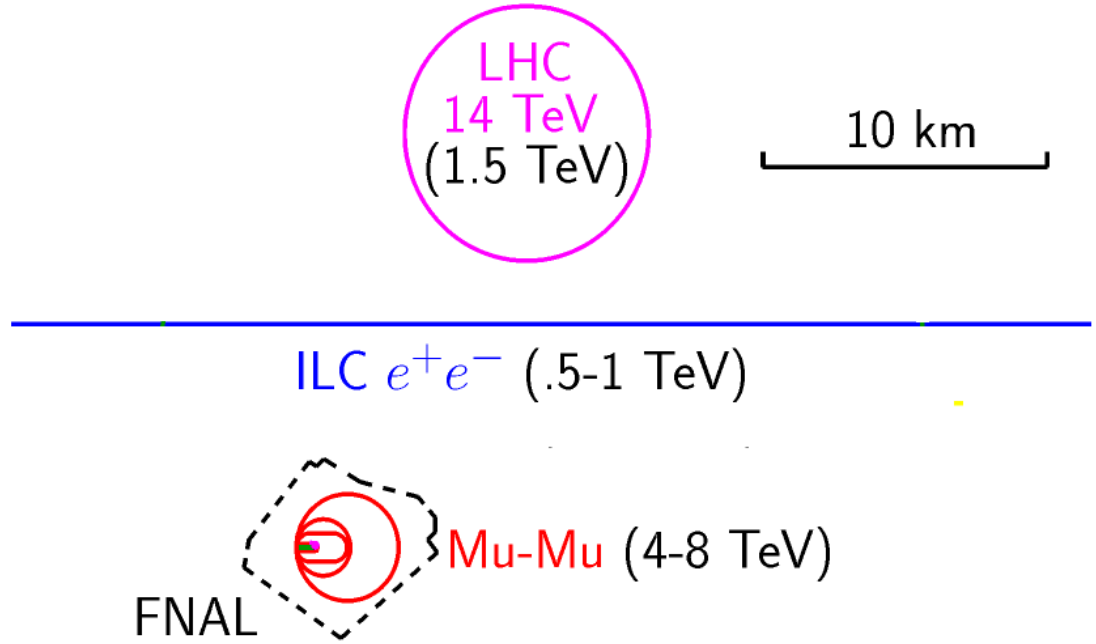
Skrinsky

Neuffer

Proposed by Budker in 1969, with the needed ionization cooling by Skrinsky and Parkhomchuk in 1981. Neuffer gave an outline in 1983. The US Muon Collider Collaboration was formed in 1997. FNAL formed its Muon Collider Task Force in 2006. Much Progress has been made.

Why Muons?

- Muons are point like, so their full energy counts
- And they can be bent, making their colliders much smaller

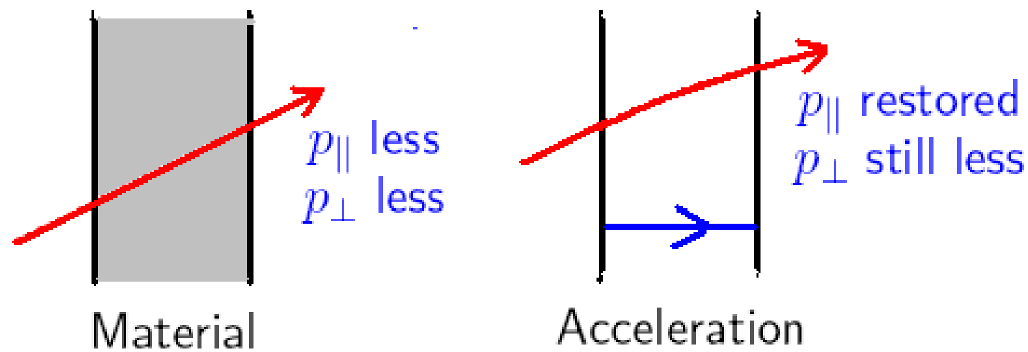


But life is hard

- Muons are made very diffusely
- And they do not live very long

The problem, as with antiprotons, is cooling the muons.

Stochastic cooling is too slow, so we have to use Ionization Cooling.



A complete scheme has been outlined, but there is much design and experimental work remaining.

The End

- Thanks to those that helped me
- Apologies to those I left out
- Acknowledgments to
  - Sessler and Wilson's "Engines of Discovery"
  - Crease's "Making Physics"
  - "AGS 20" BNL 51377

Palmer

Blewett/Livingston/Samios Plot