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# High Energy Colliders

## Informal Introduction & Ph.D. Opportunities

Rama Calaga  
April 13<sup>th</sup>, 2007

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# Particle Accelerator School

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[uspas.fnal.gov](http://uspas.fnal.gov)

Every 6 Months, 2 Week Courses:

June 4-15, 2007 – Michigan State University

January 14-25, 2008 – University of California, Santa Cruz

**Financial Support Available Via Fermilab**

Note: Earn 3 Hrs of Credit: “Possibility” of satisfying Breadth Courses (Inquire with Phys. Dept)

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# First Accelerator

© Original Artist

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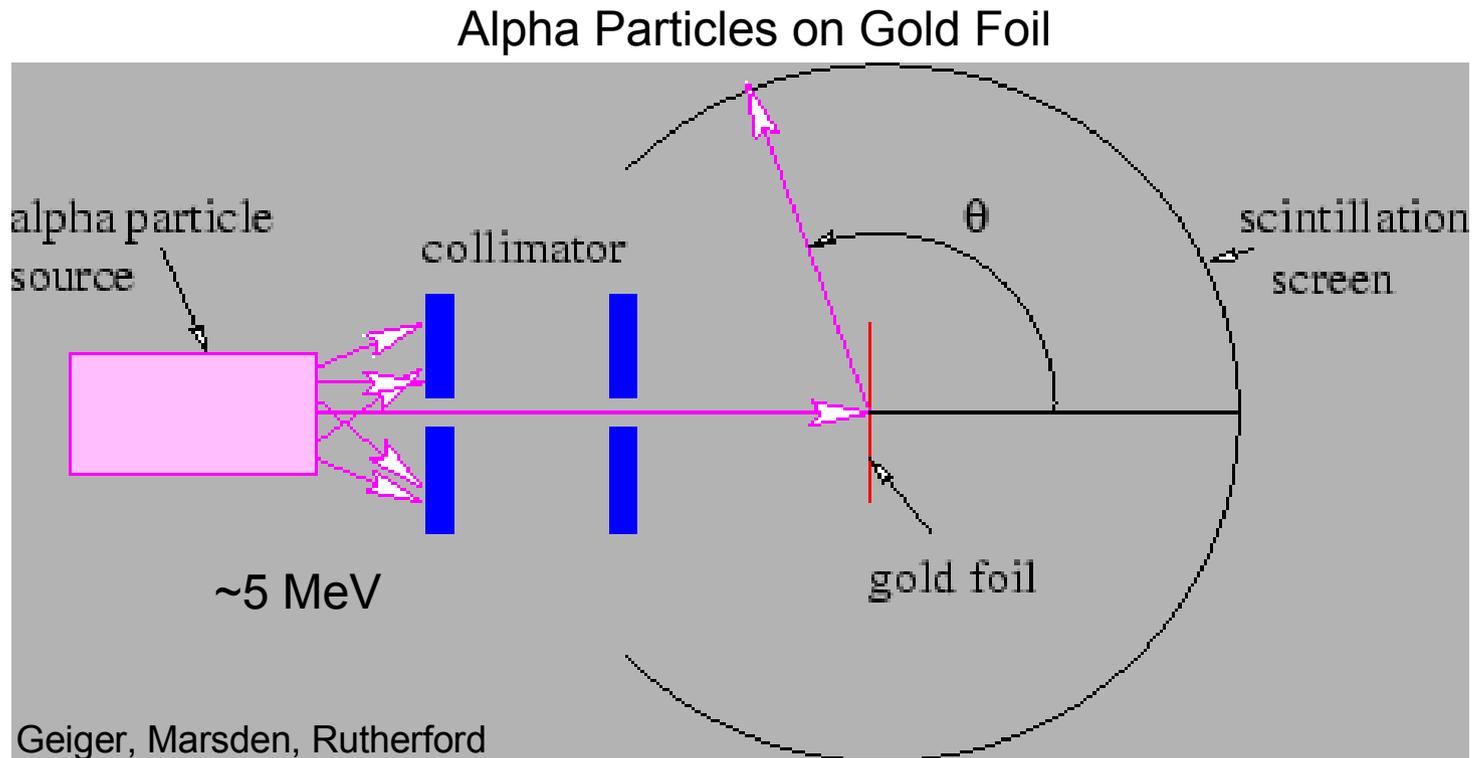
[www.CartoonStock.com](http://www.CartoonStock.com)

Okay... ready!  
three,... **THROW!**



Before the linear accelerator

# First Real Accelerator (circa 1909)



Most  $\alpha$ -particles passed right thro', a few which scattered off with **large angles**

Rutherford explained the observations with an atomic structure which is mostly empty with central core (nucleus) that is positively charged.

Circa 1932: Cockcroft & Walton accelerate protons using 800 kV drift tube  
 $p + Li \rightarrow He + He$

# Hadron & Lepton Colliders

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Subsequent developments:

Van de Graff, Cyclotrons, Linear Accelerators, Weak Focusing, [Strong Focusing](#)...

Birth of Synchrotron (1944): McMillan & Veksler discovered the principle of phase stability  
(*Physics Today April 2007 Issue, BNL Cosmotron – First Synchrotron*)

Courant-Syndner (1952): Strong-Focusing – Pair of Lenses ( $f_1 = -f_2$ )

$$1/F = d/f_1 f_2$$

## Leptons (High Precision)

Linear Accelerators, B-Factories

Light Sources, Free Electron Lasers, ERLs

$\mu$ -Colliders (lifetime problem), Others...

## Hadrons (Highest Energies)

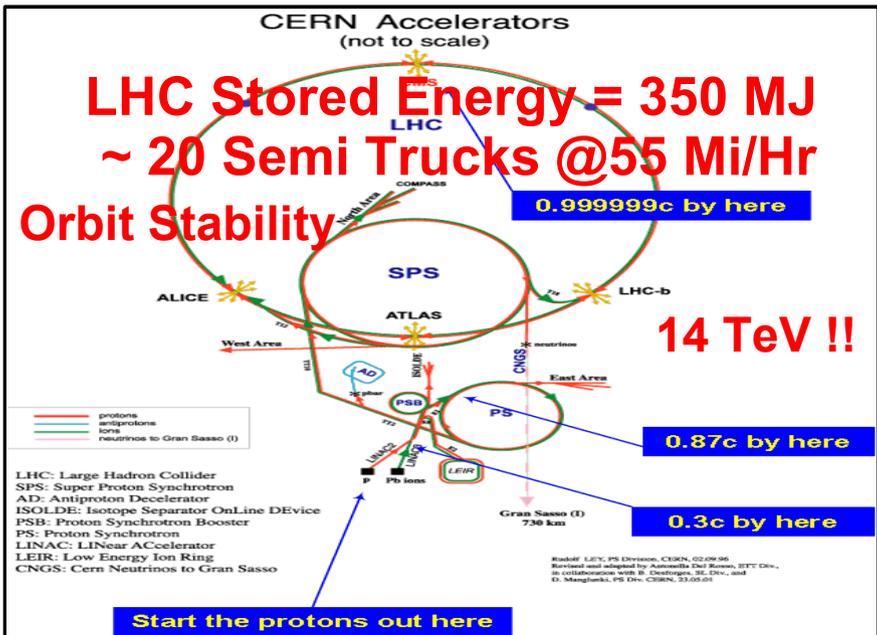
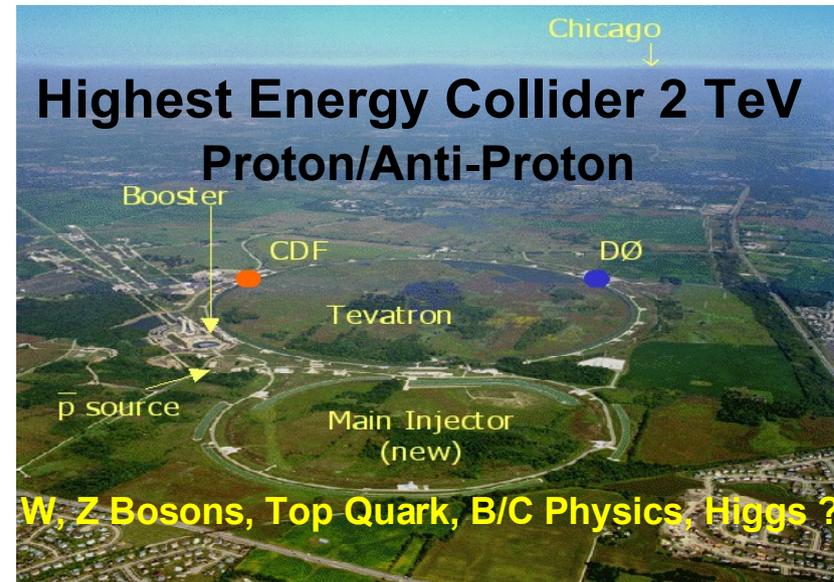
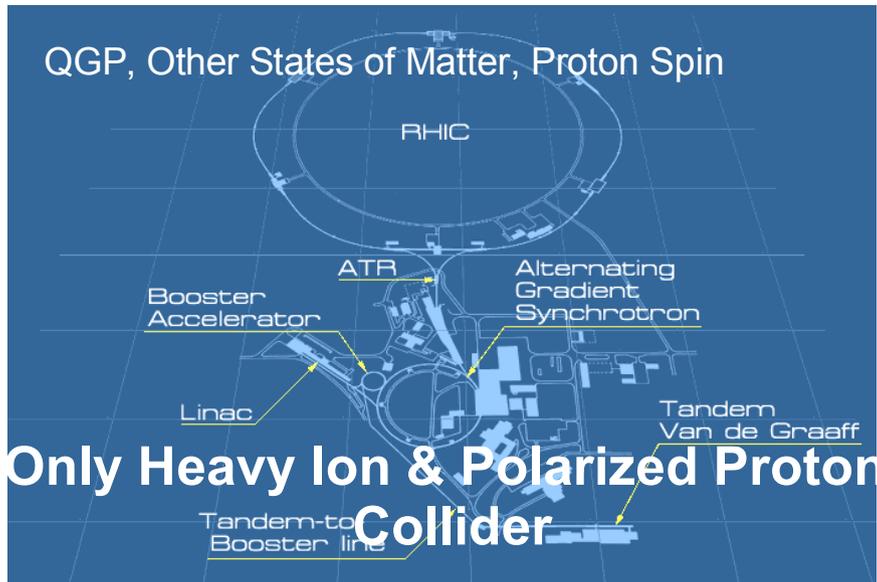
Proton/Antiproton

Light/Heavy Ions

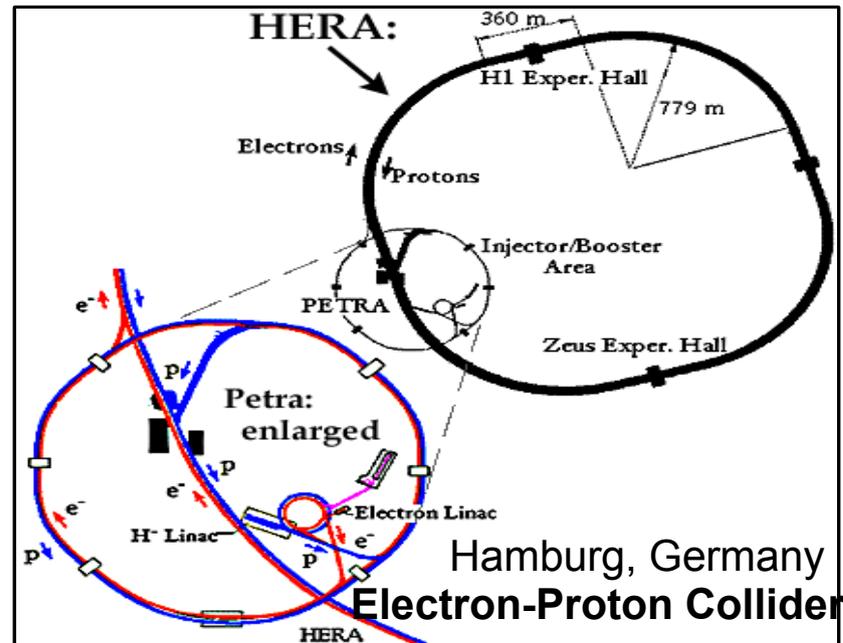
Medical Accelerators

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# Some Hadron Colliders

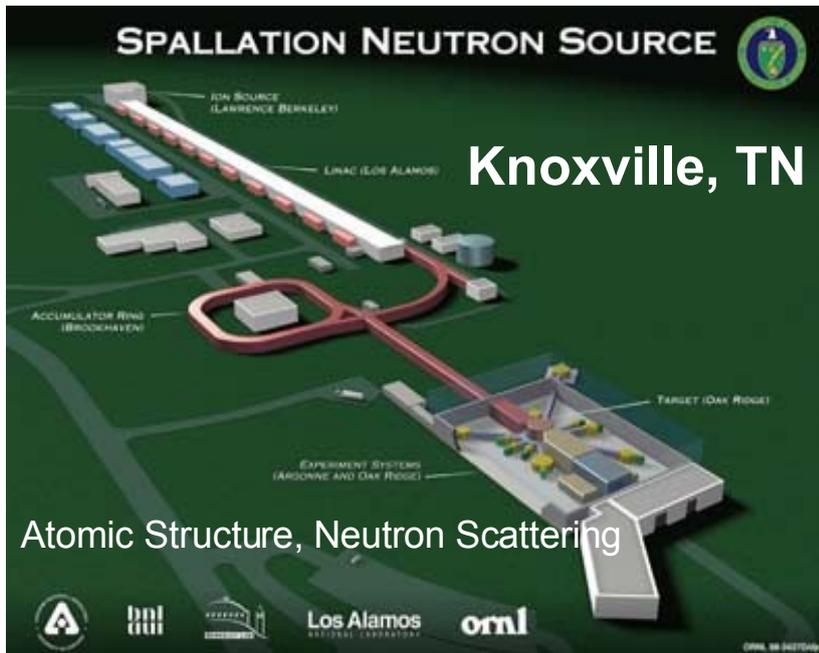
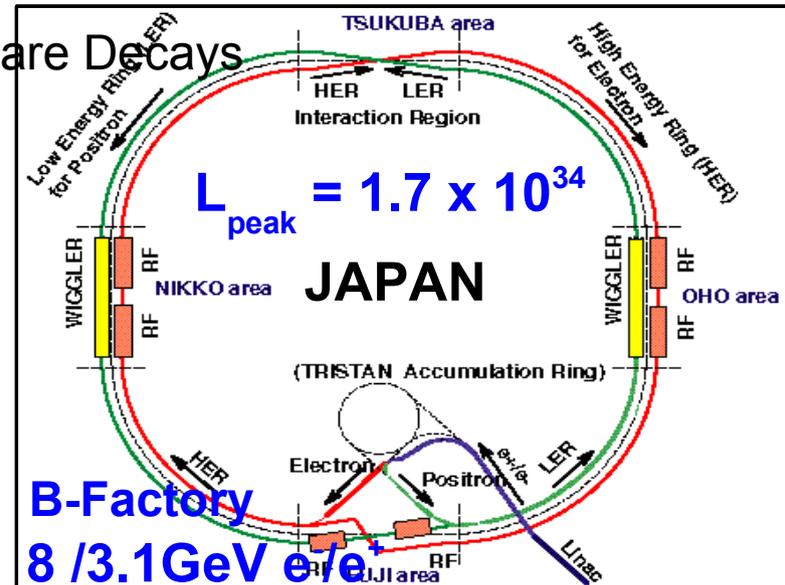
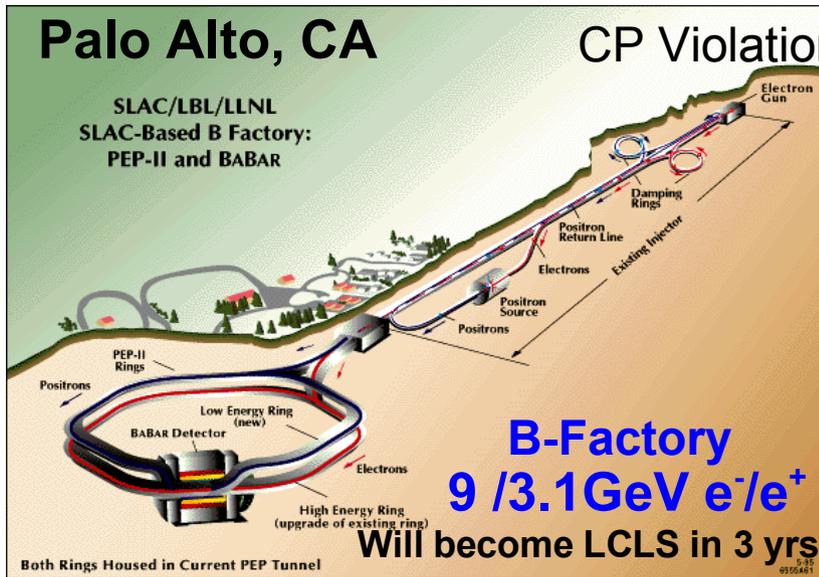


Higgs, Supersymmetry...



DIS, Proton Structure, QCD...

# Some Lepton Colliders



# Figures of Merit

Probe smaller lengths  $\rightarrow$  Higher Energy

$$\Delta r \propto \lambda = \frac{h}{p}$$

For Example: 1 GeV = 1 fm (quarks, electron  $< 10^{-18}$  m)

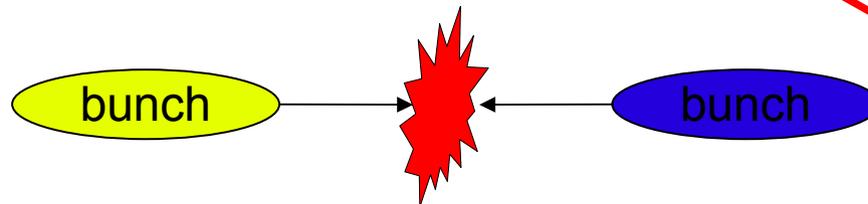
Higher Luminosities:

$$L = \frac{1}{(4\pi)} f_0 N \frac{n^2}{\sigma^2}$$

Number of Bunches

Particles/Bunch

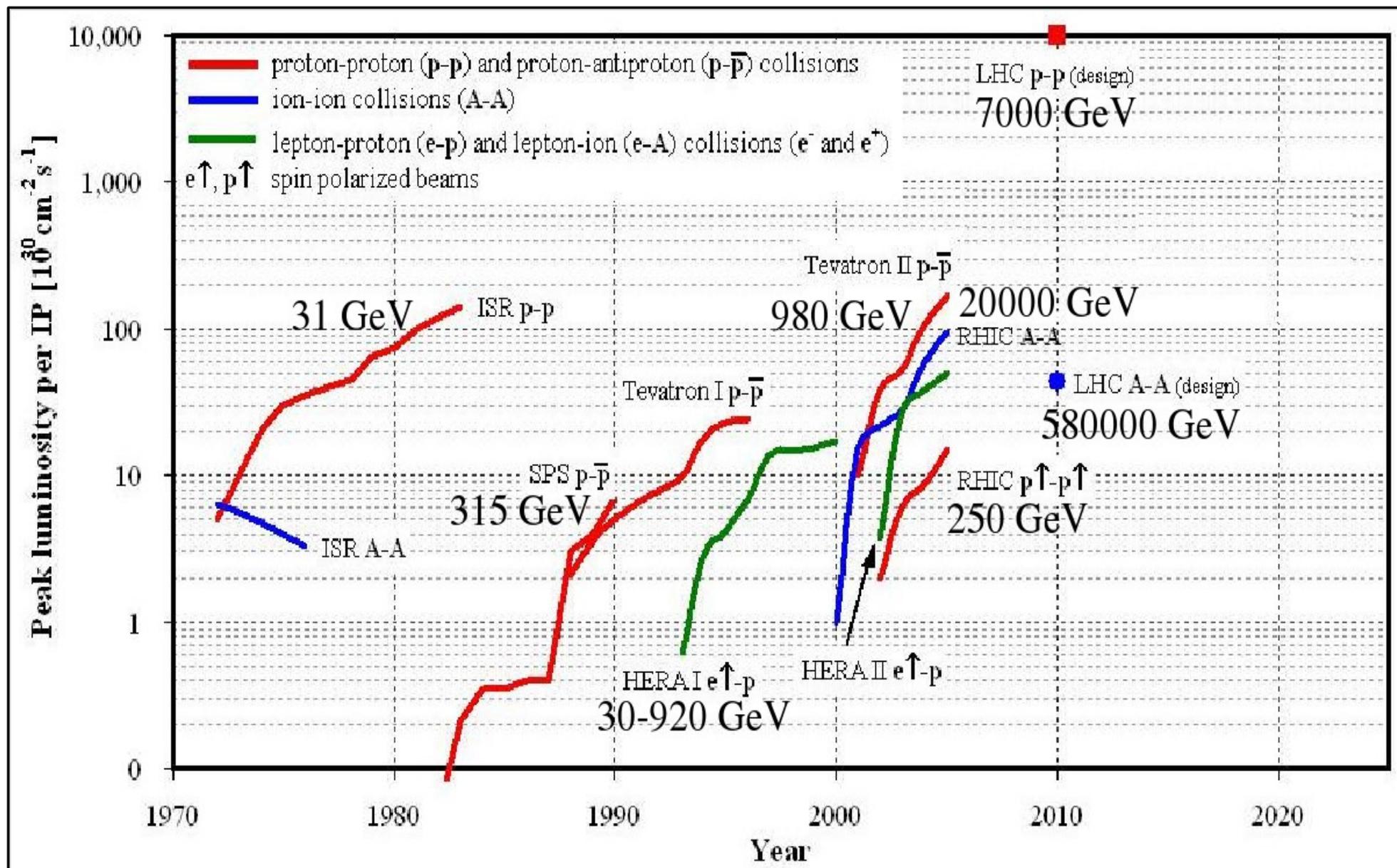
Beam Size



Lifetime:

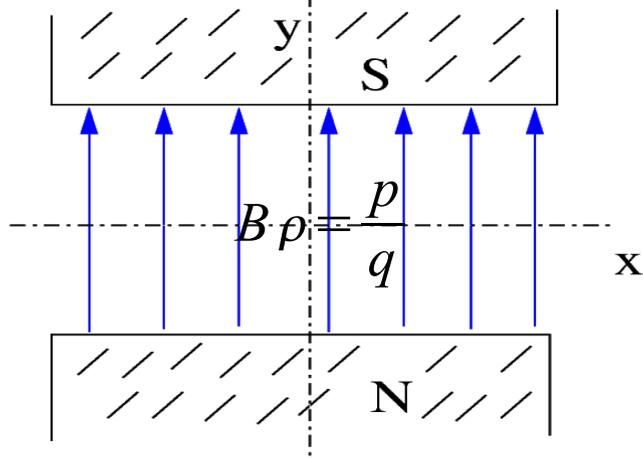
Touschek lifetime, Intra-Beam Scattering, Residual Gas (Vacuum), etc...

# Peak Luminosities

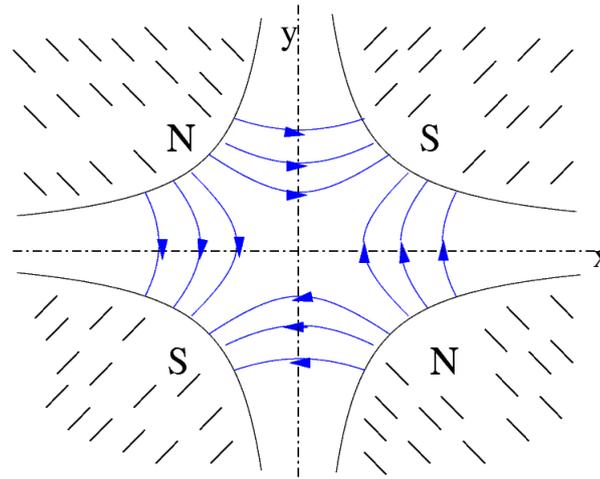


# Accelerator Magnets

## Dipole

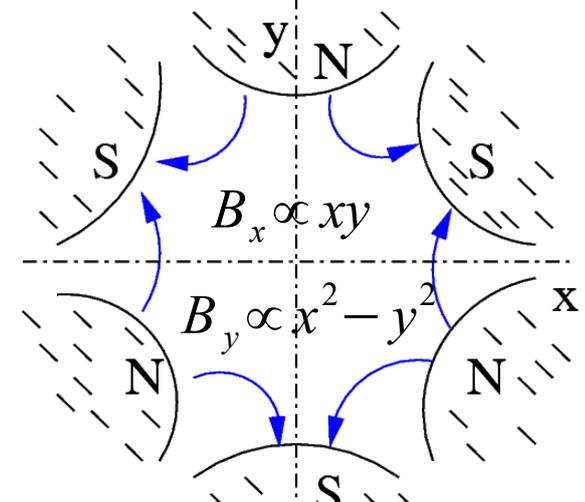


## Quadrupole



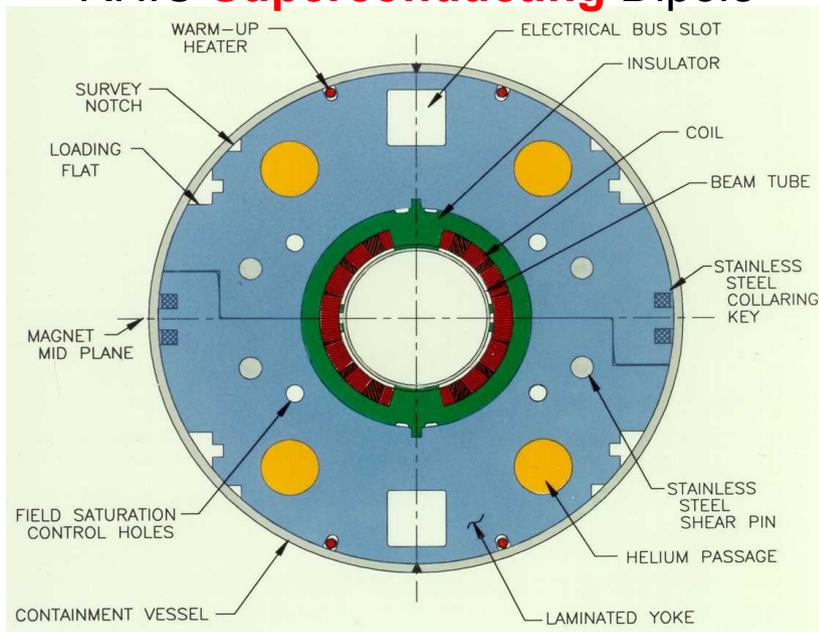
Linear w.r.t Transverse Coord.

## Sextupole

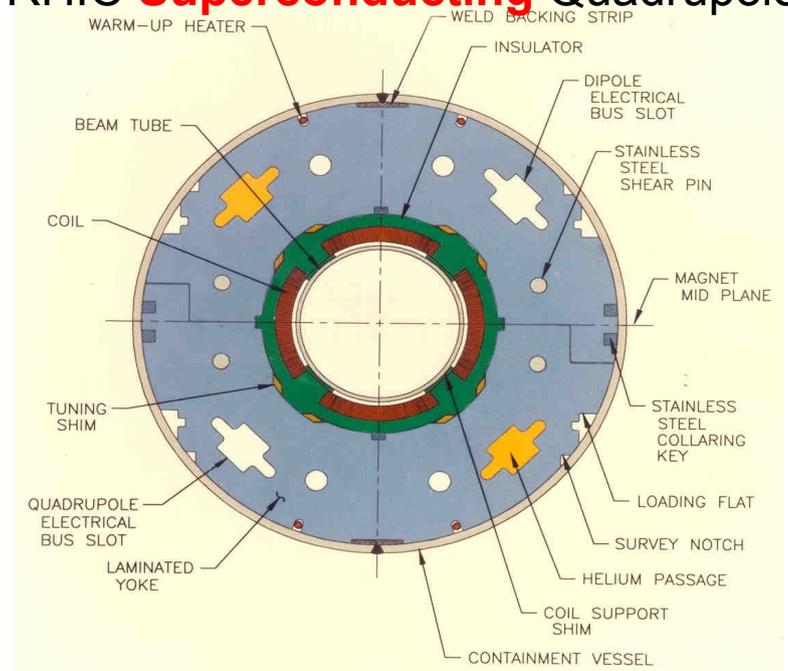


Quadratic w.r.t Transverse Coord.

## RHIC Superconducting Dipole



## RHIC Superconducting Quadrupole



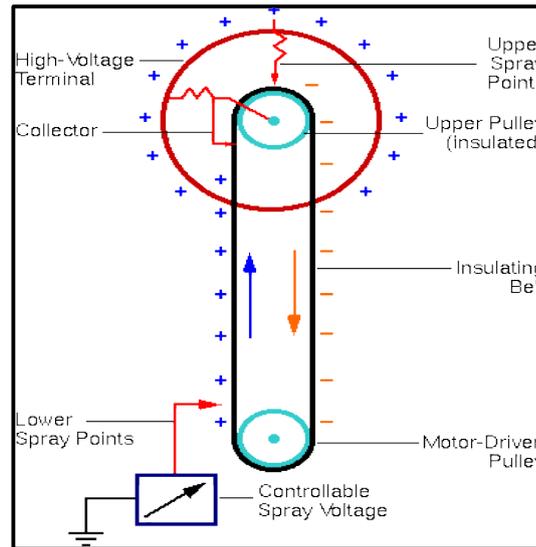
# Accelerating Structures ( $dp/dt = eE$ )

## Cockcroft Walton

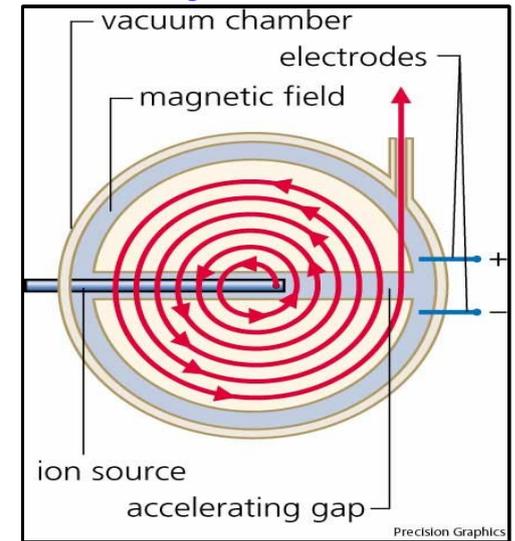


Capacitive Charging & Discharging  
0.75 MeV at FermiLab

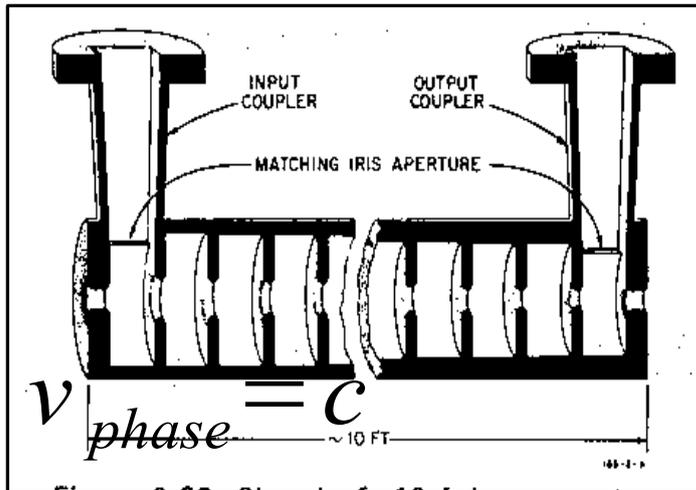
## Van De Graaff



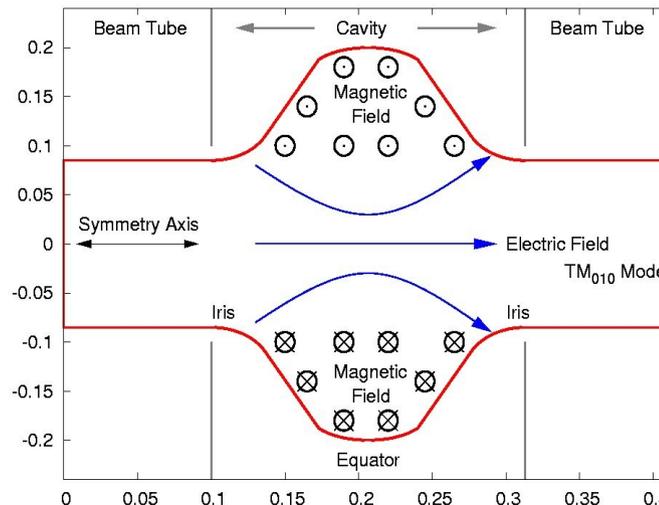
## Cyclotron



## Traveling Wave Structure



## Resonant Cavities



## Superconducting Cavities

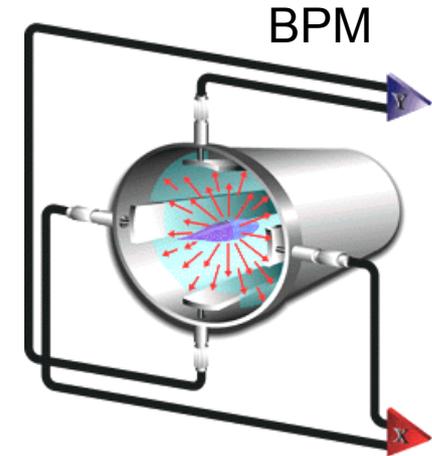


Many other exist: Coaxial, ferrite loaded, etc...

# Instrumentation

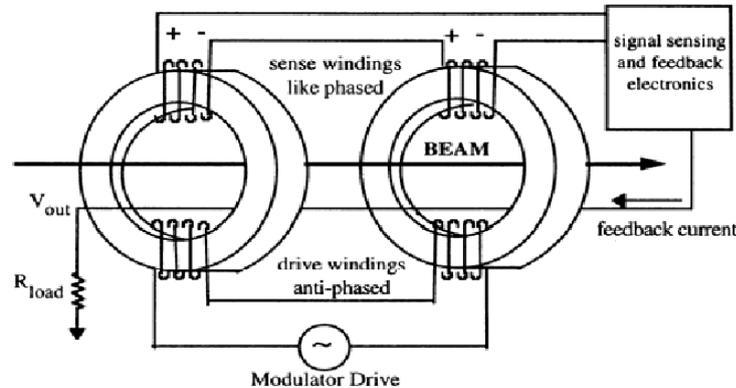
## Beam Position

Closed Orbit, Betatron Oscillations (Tune, Optics, Coupling)  
Momentum Dependence (Dispersion, Chromaticity)



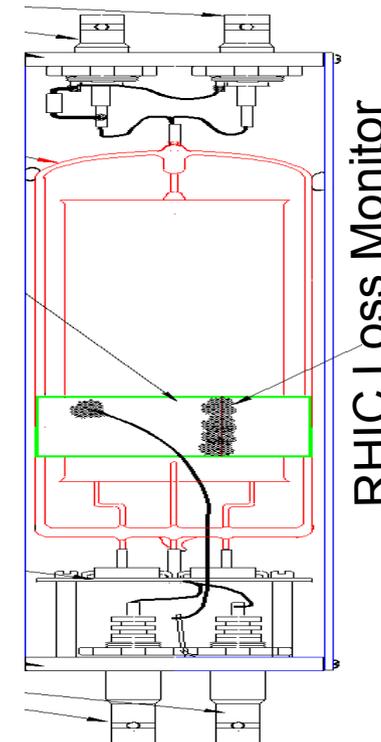
## Beam Current

Intensity, Losses



## Beam Emittance

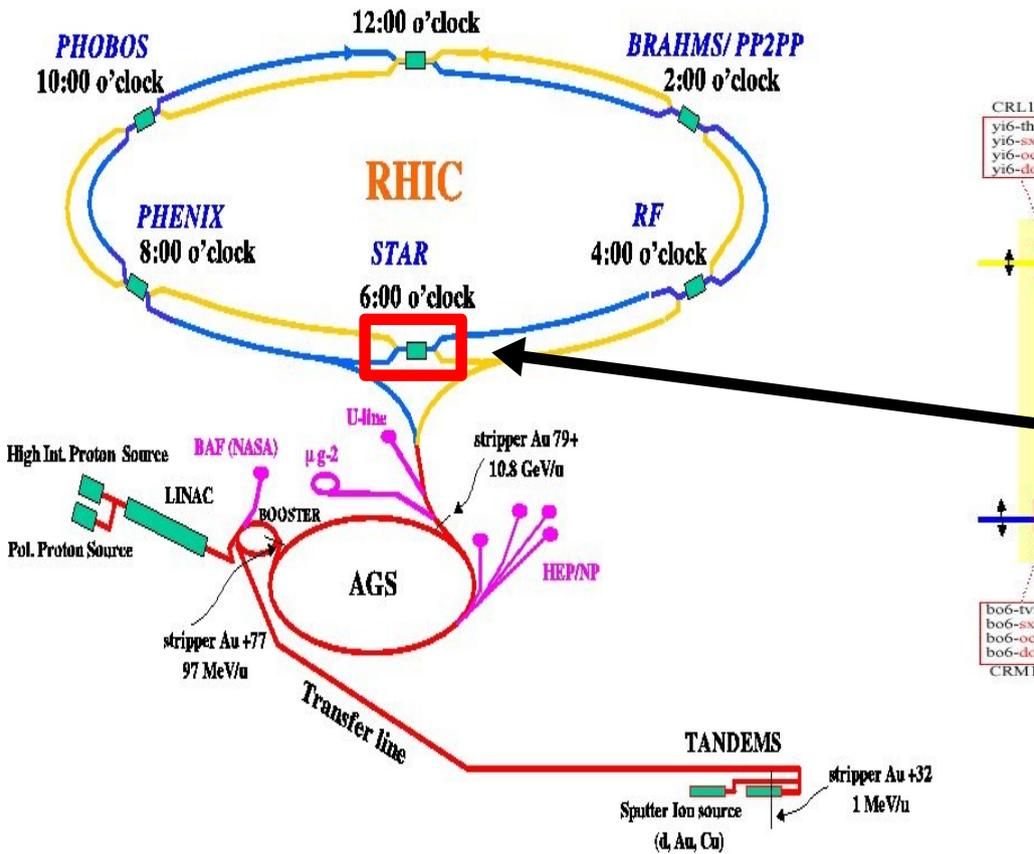
Transverse (Wires, Screens, Synch Radiation)  
Longitudinal (bunch shape)



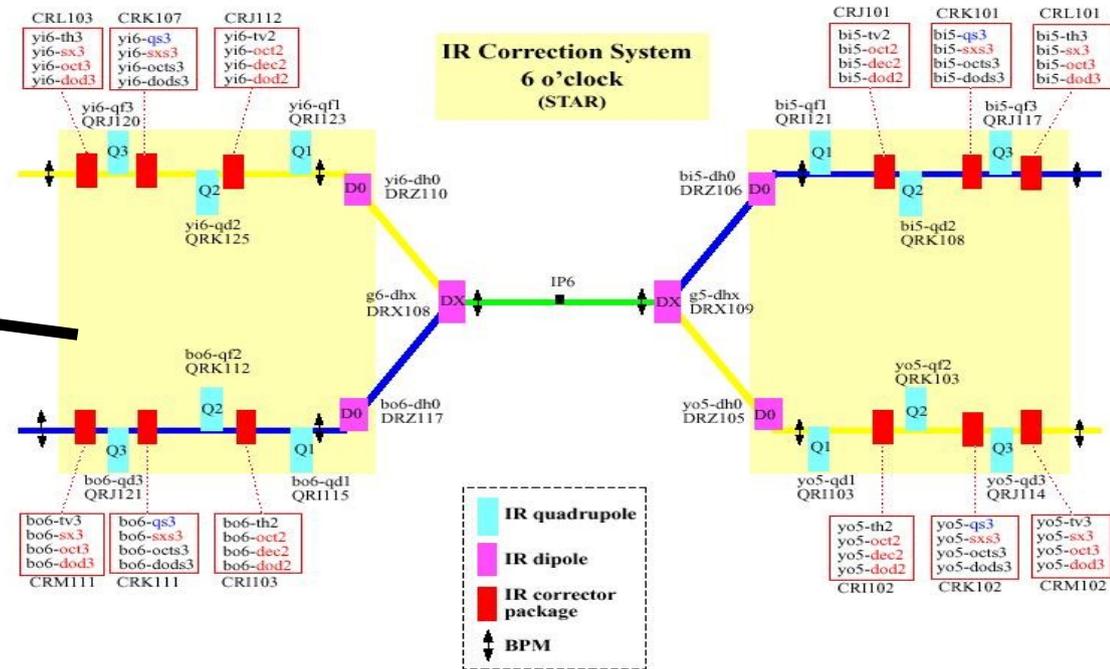
## RF Issues

Synchrotron Tune (Revolution Freq)  
Potential Well

# The RHIC Complex



## Interaction Region



## RHIC Ring:

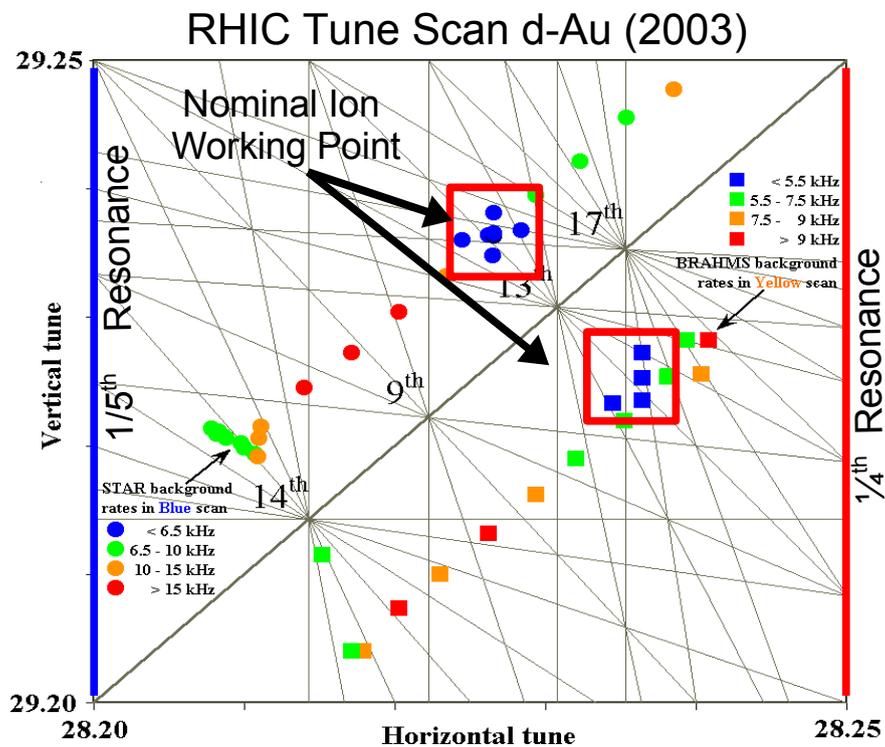
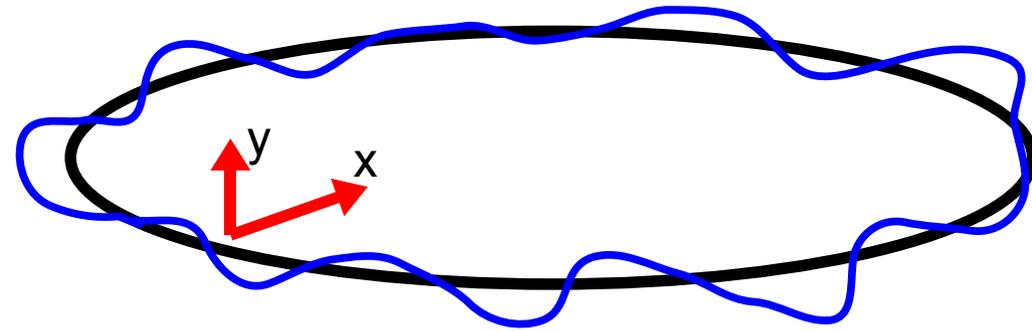
Six arc sections FODO Lattice ~ 82° deg Phase Advance

Six Interaction Regions (Triplet Focusing + Dispersion Suppressor)

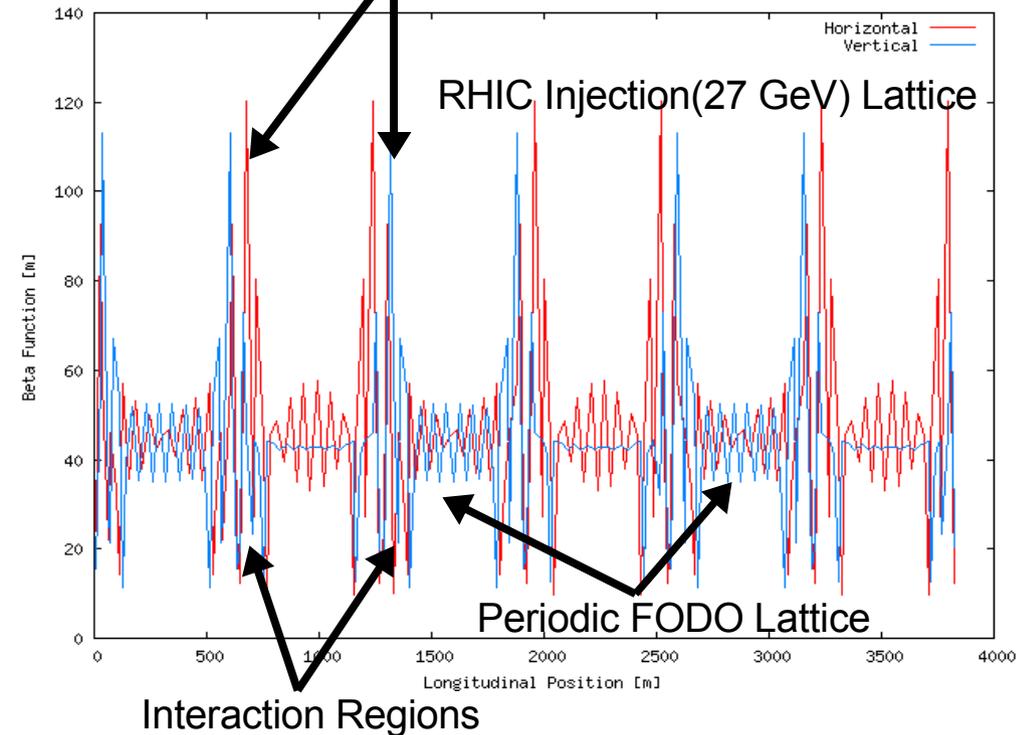
Non-Linear corrector package

# Linear But Critical Stuff

- Closed Orbit (long term stability), Acceptance
- Betatron Tune & Chromaticity
 
$$mQ_x + nQ_y = p$$
- Linear Optics & Coupling

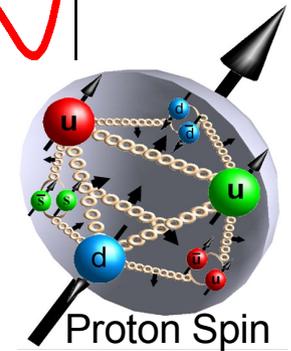
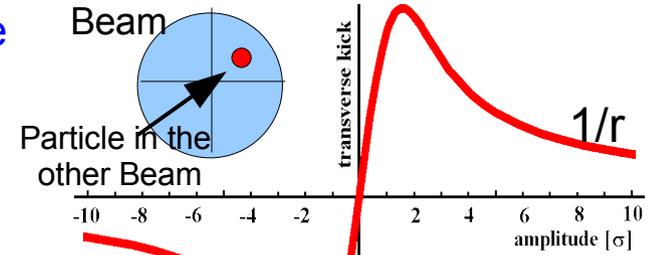


$$x(s) = \sqrt{(2J\beta(s))} \cos(2\pi Q + \phi(s) + \phi_0)$$

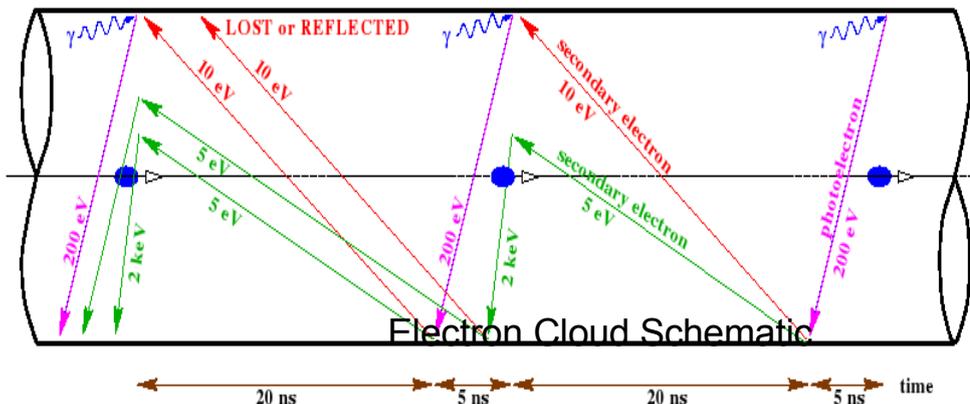
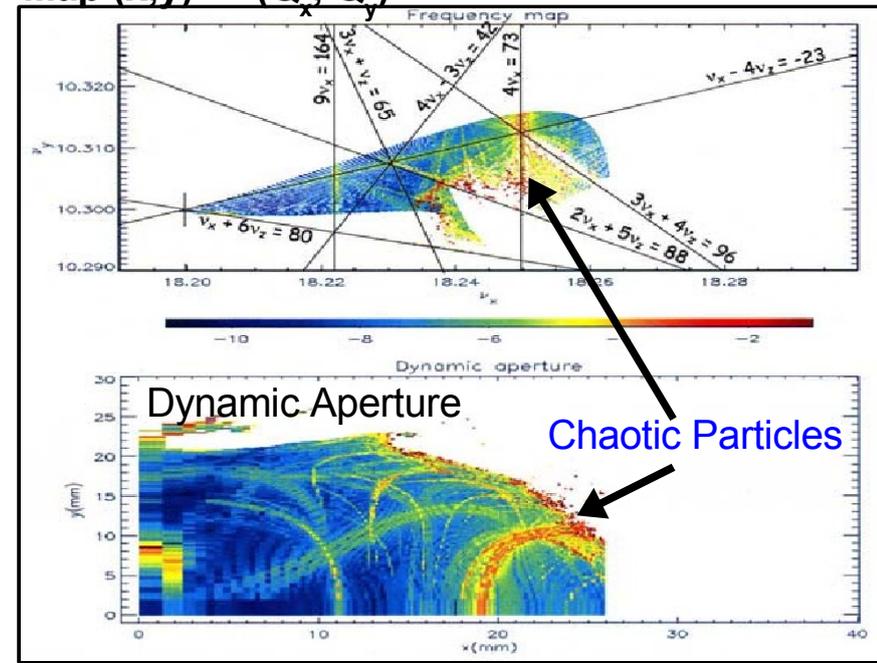


# More Advanced Stuff

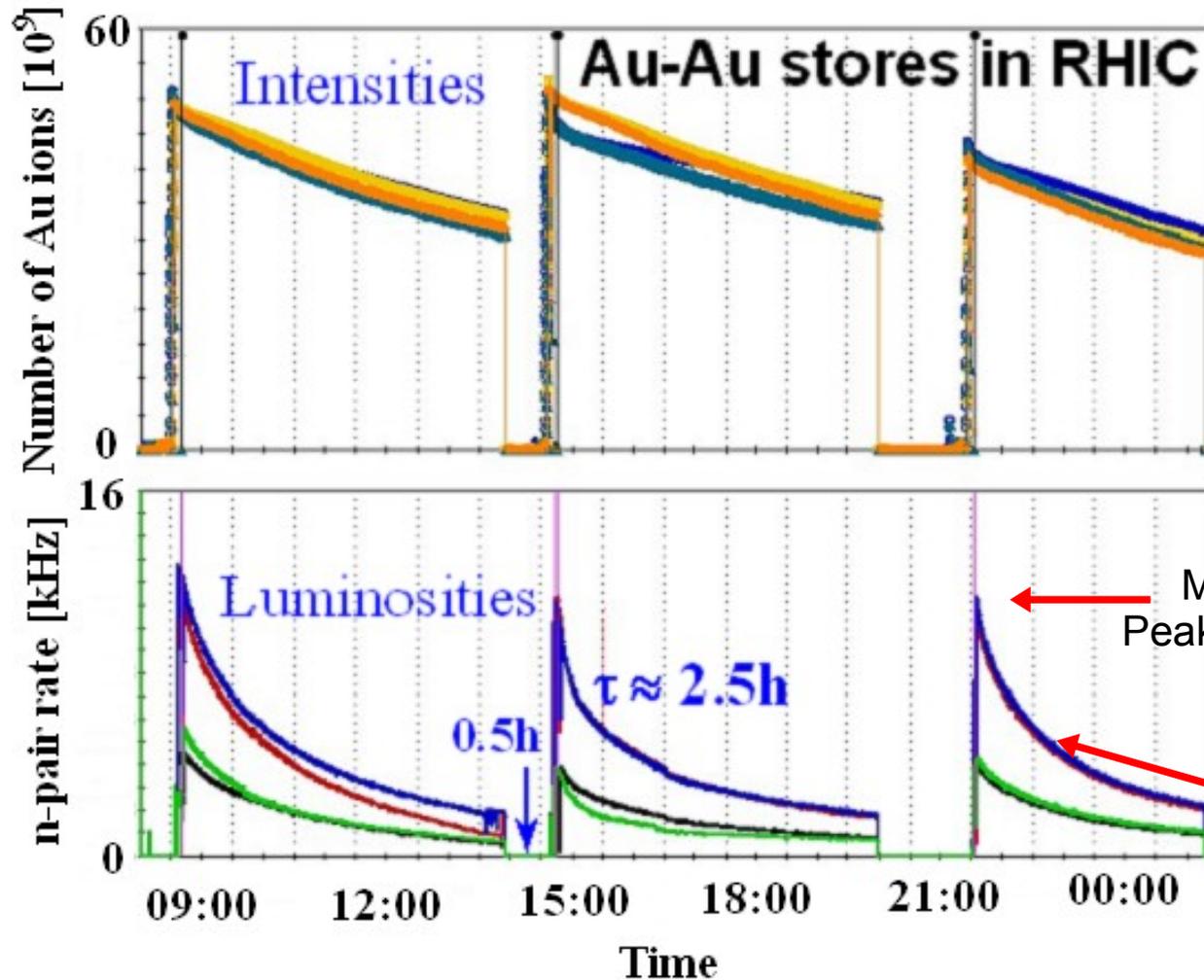
- **Beam-Beam Forces (Diffusion & Emittance Growth, Dynamic Aperture**
- Single & Multi Bunch Instabilities, Electron Cloud Induced
- Collimation (primary, secondary, crystal)
- Ultra high field Nb<sub>3</sub>Sn Superconducting Magnets
- **Superconducting Accelerating & Crab Cavities**
- High Energy Polarized Protons & Preservation
- **Electron & Stochastic Cooling**
- High current photo-cathodes (laser driven)
- Advanced Acceleration Techniques (Plasma & Laser)
- Theoretical Studies
  - Collective Instabilities & Wakefields
  - Electron Cooling Dynamics
  - Large Scale Particle Tracking, Using Taylor & Lie Maps



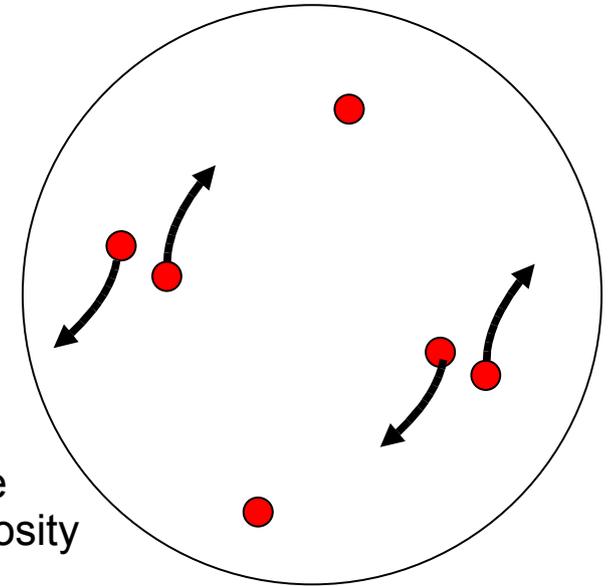
Map  $(x,y) \rightarrow (Q_x, Q_y)$



# Intra-Beam Scattering



Multiple small angle coulomb scattering

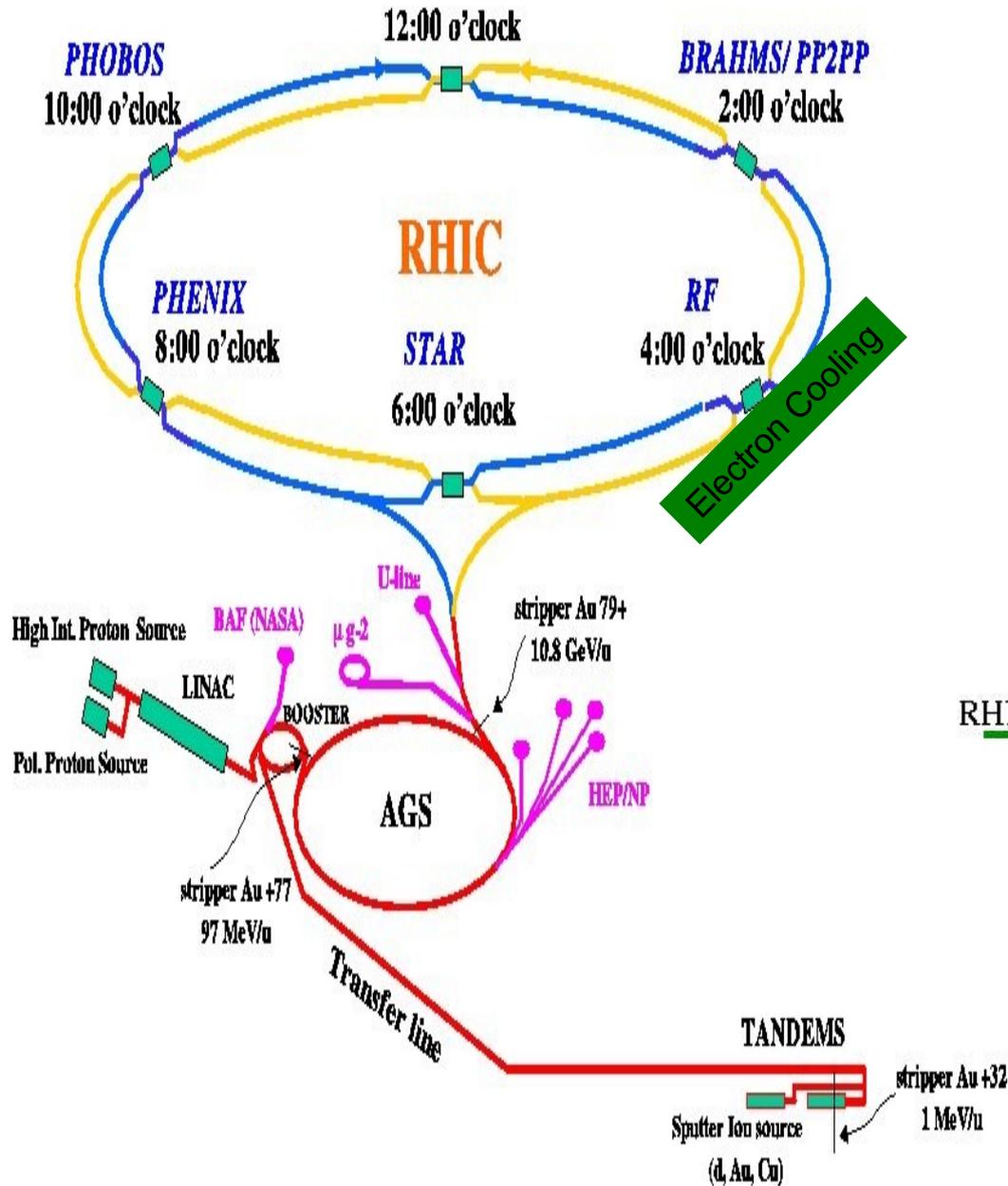


Reduce particle loss & beam size growth

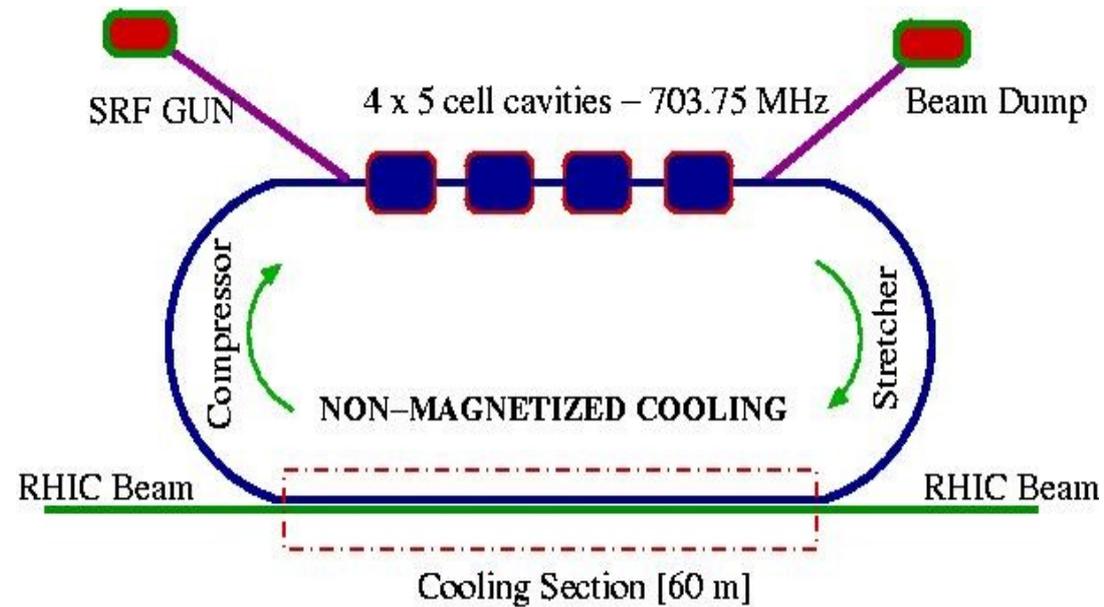
Dominant factor for Ion particle loss & beam size growth

Solution: Submerge "cold" electrons into the ion-bunches

# Electron Cooling of Ion-Beams

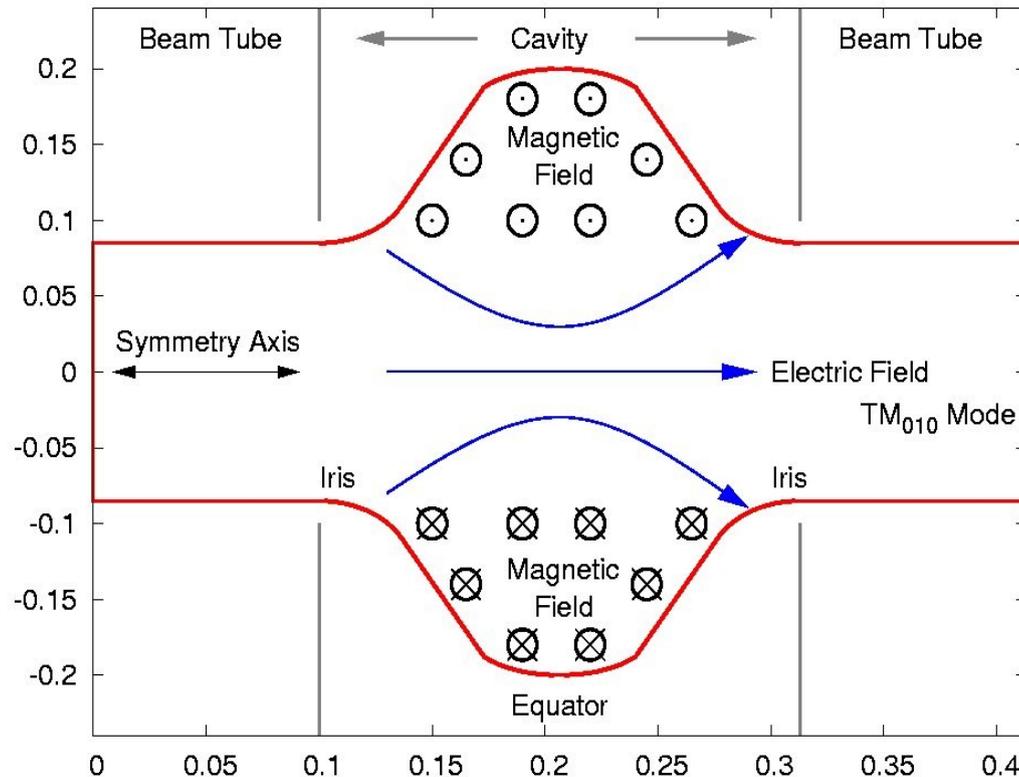


Beam Energy **Several MegaWatts**  
Need **Energy Recovery**



First high energy bunched cooling with ultra-high current electron beam using **ENERGY RECOVERY LINACS**

# Name of the Game: Superconducting



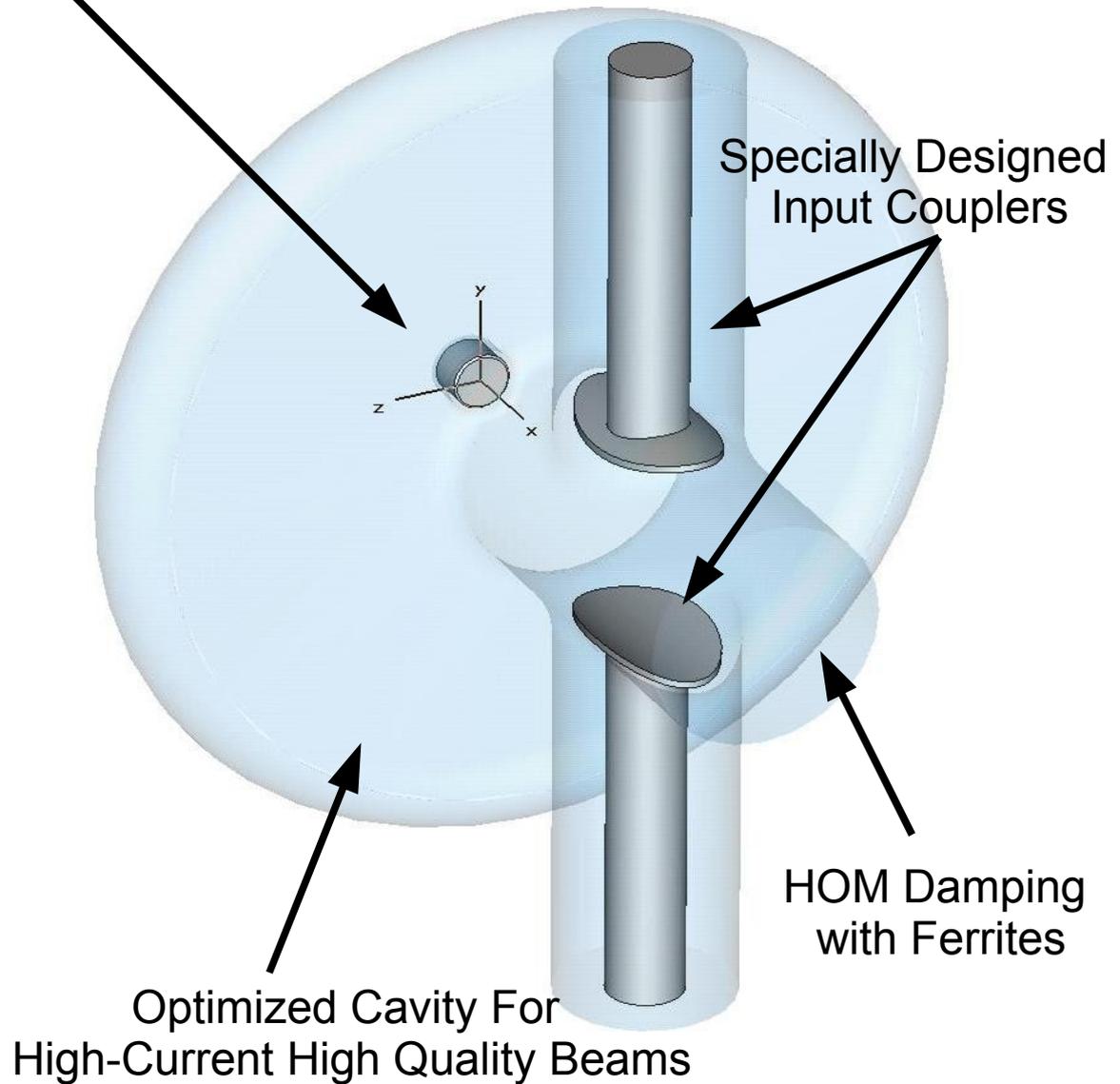
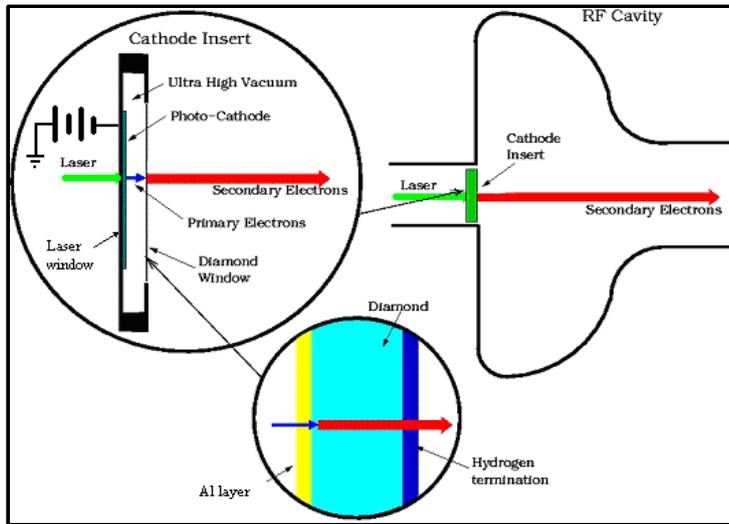
## Several Issues:

- EM Field Analysis (FEM,FD)
- Multipacting (Elliptical Shape)
- Higher Order Modes
  - Cavity shape, Damping
- Thermal Breakdown
  - High Purity Niobium
- Field Emission
  - BCP, Baking, HPR

| Option | Normal Conducting | Super Conducting   |
|--------|-------------------|--------------------|
| Q      | $2 \times 10^4$   | $2 \times 10^{10}$ |
| R/Q    | 900               | 330                |
| P/L    | 500 kW/m          | 1.5 W/m            |

# SRF Injector Gun (703.75 MHz)

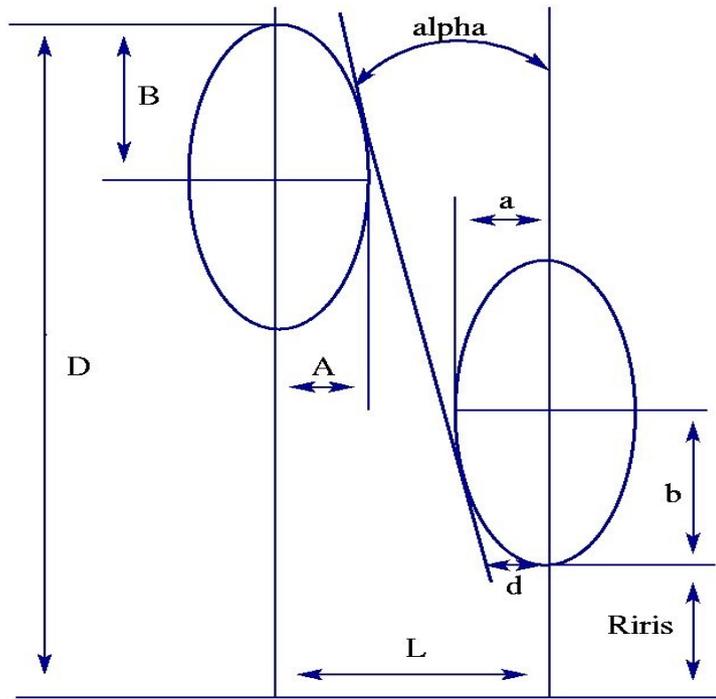
## Diamond Amplified Cathode



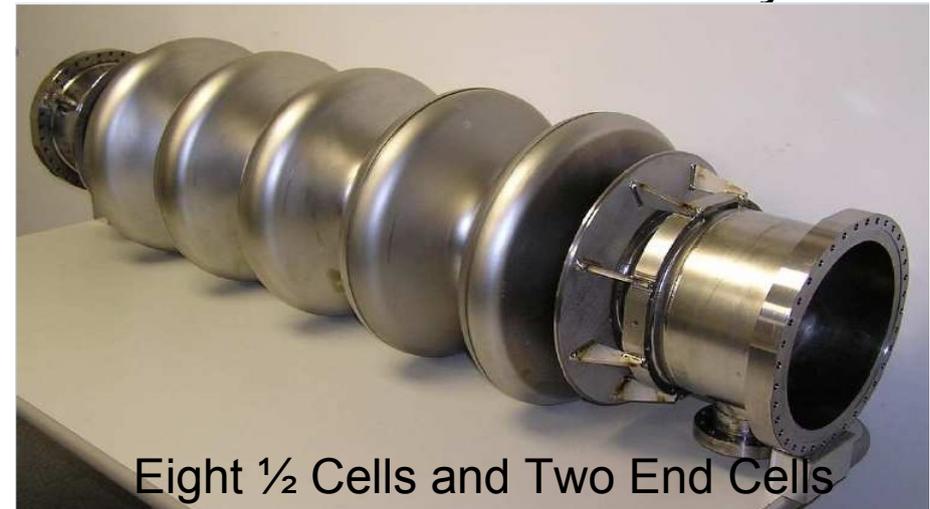
## Experimental Setup for Dimaond Amplification



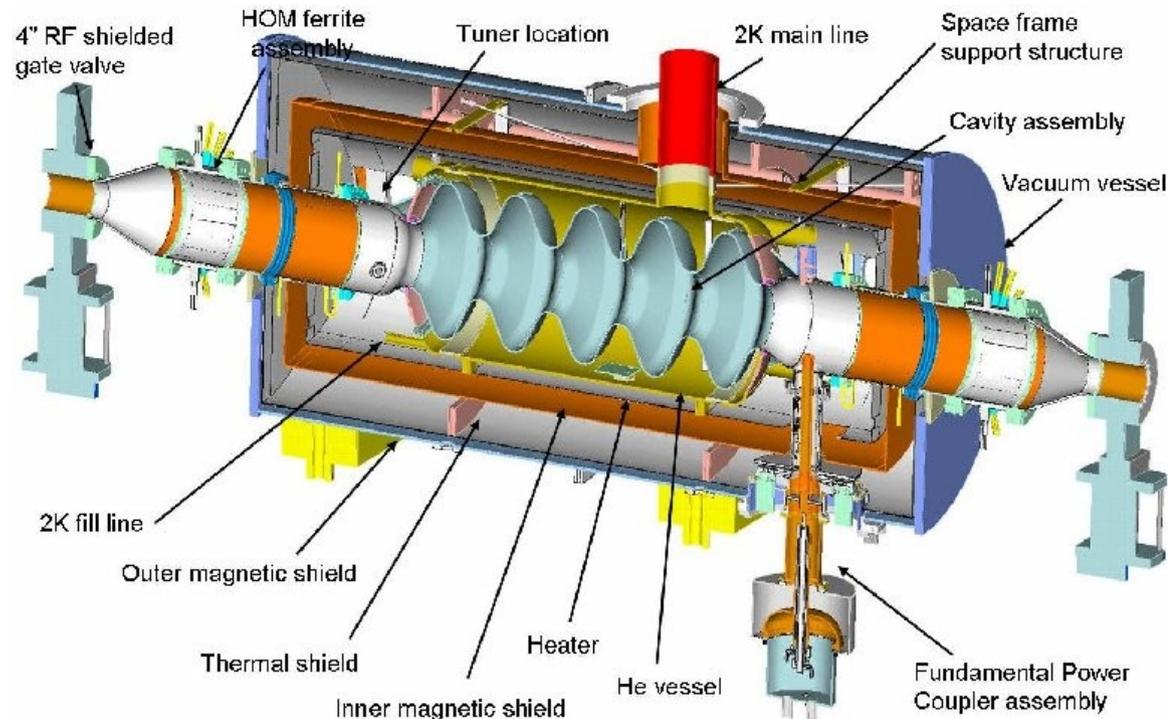
# Accelerating Cavity (703.75 MHz)



## BNL Five-Cell Cavity

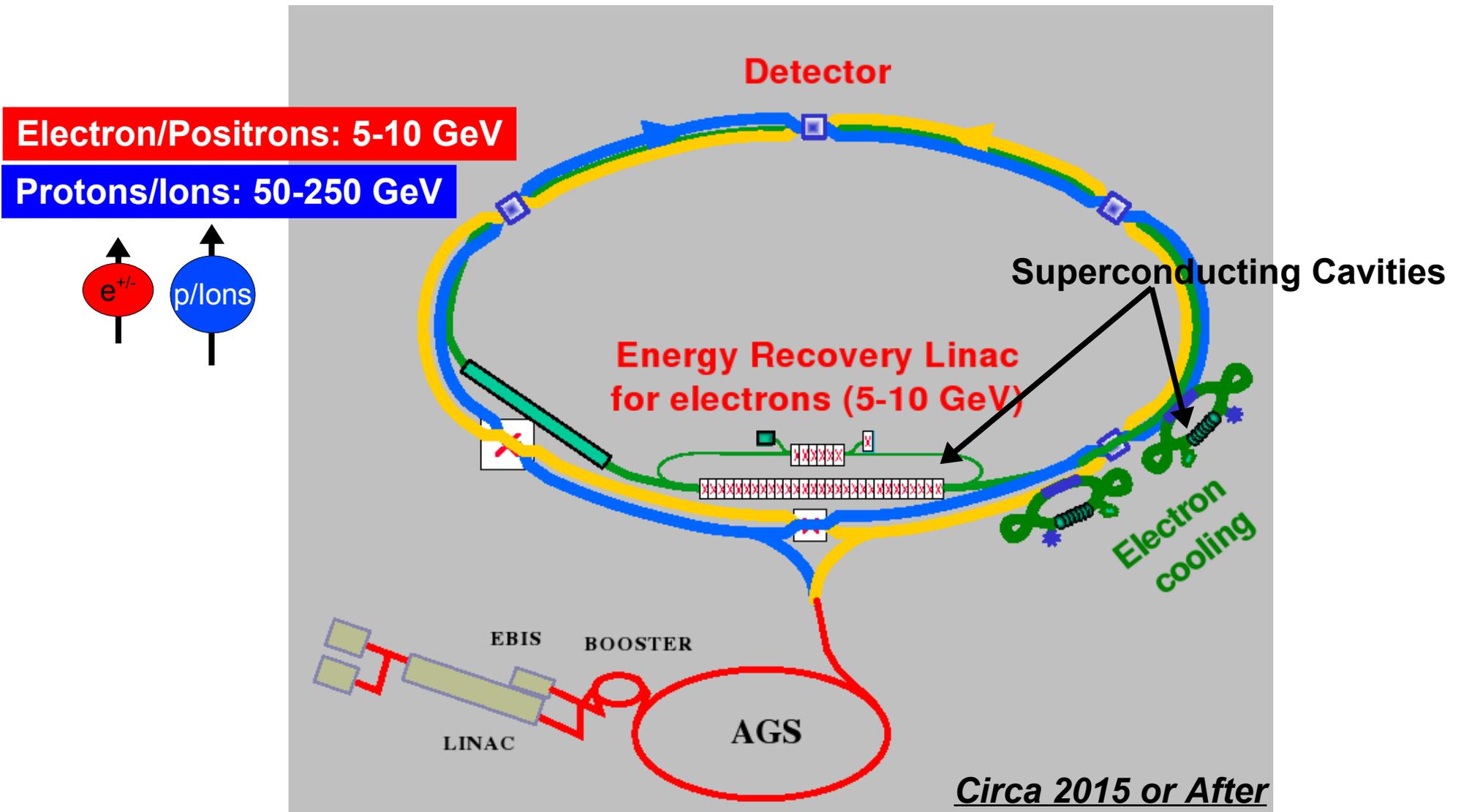


- Mechanical Analysis (Lorentz Forces, Tuning, etc..)
- Surface Treatment (Surface Physics)  
Chemical & Electro Etching  
Vaccum Baking
- Cryogenics (2K Superfluid He)

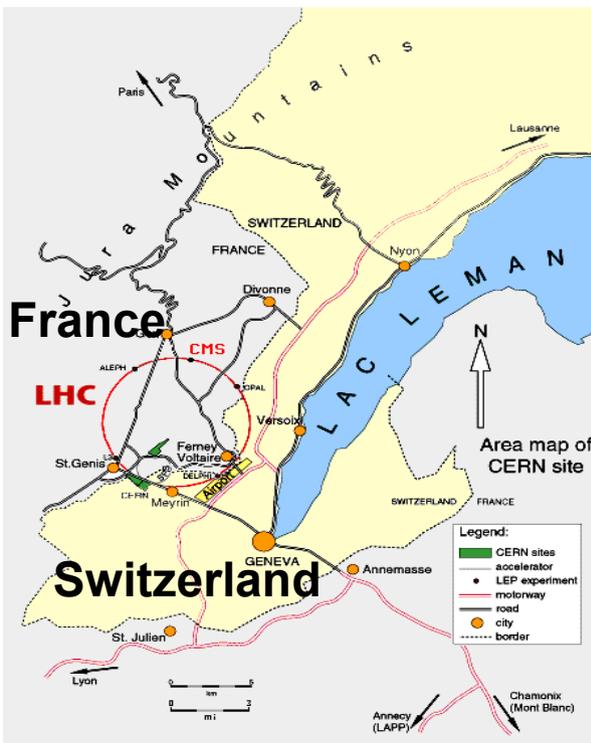


# Future: Electron-Ion Collider

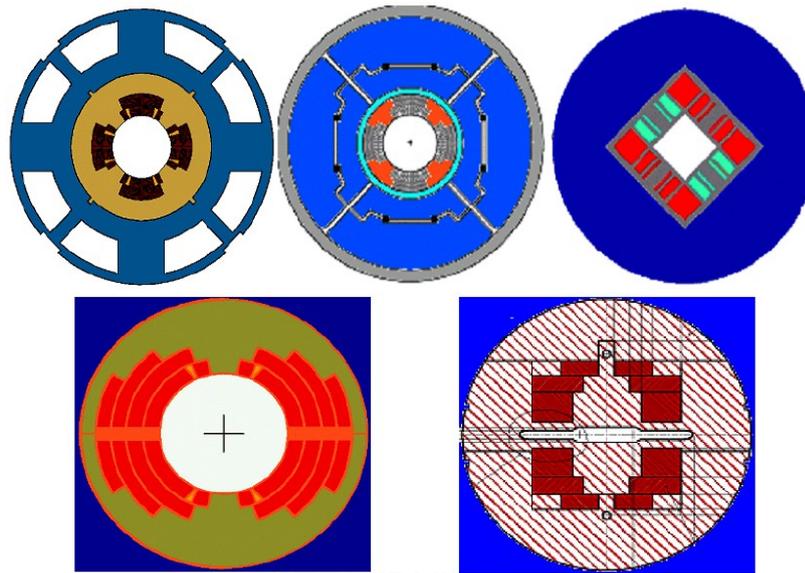
A high luminosity polarized  $e$ - $p$ / $He$  and unpolarized  $e$ - $A$  collider to study the hyperfine structure of the nucleon including (spin and flavor) and to explore nuclear matter at high parton densities.



# US-LHC (LARP)



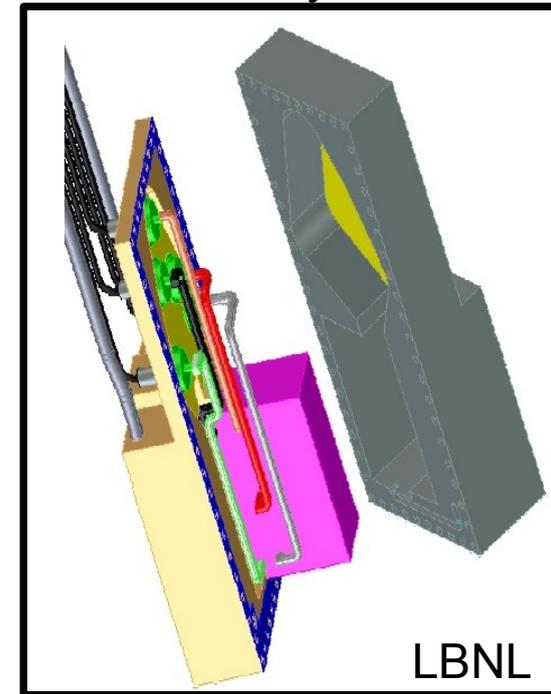
## Magnet R&D For LHC Upgrade



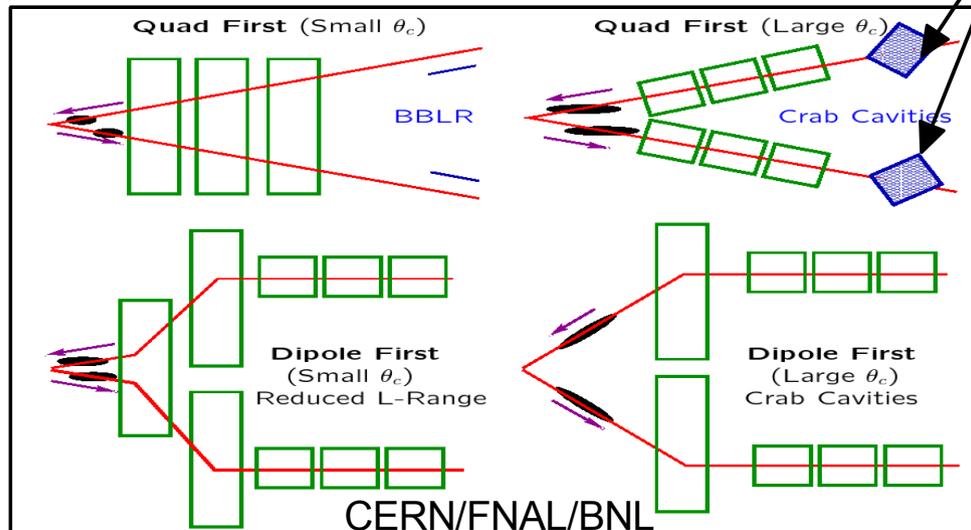
CERN/BNL/LBNL

## Crab Cavities

## Luminosity Monitor

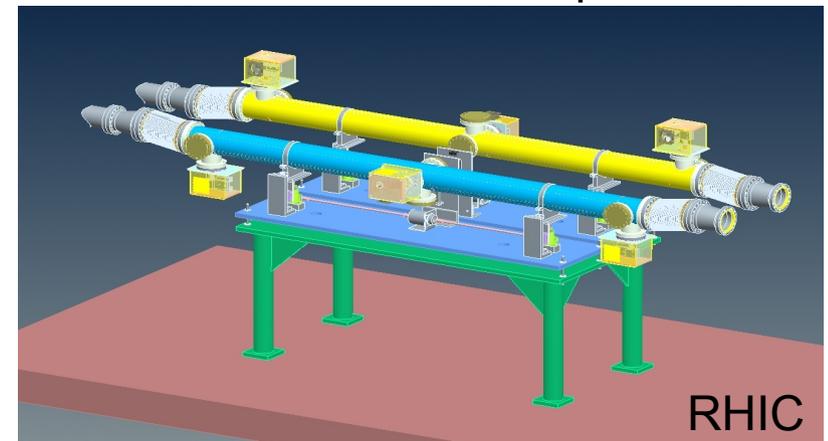


## IR Design For Upgrade



CERN/FNAL/BNL

## Beam-Beam Wire Compensators



LHC Commissioning & IR Upgrade

# Conclusions

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- Multidisciplinary & Wealth of Physics
- Good balance of theory & experiment

Good Luck Thesis Hunting !

Ack: To many people for pictures and plots

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