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Fermilab Accelerator Capabilities and Infrastructure

Robert Kephart, IARC Director

Midwest Launch of Accelerator Stewardship Test Facility Pilot Program

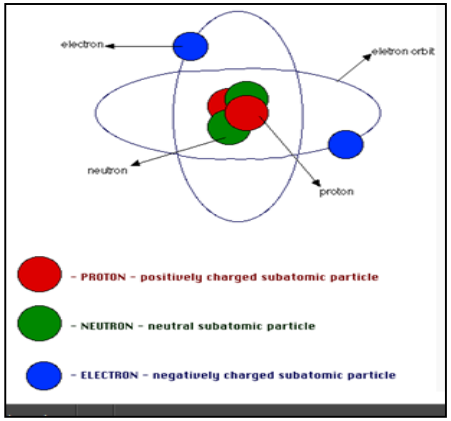
28 April 2015

What is a Particle Accelerator?

Wikipedia **"A particle accelerator is a device that uses electromagnetic fields to propel charged particles to high speeds and to contain them in well-defined beams"**

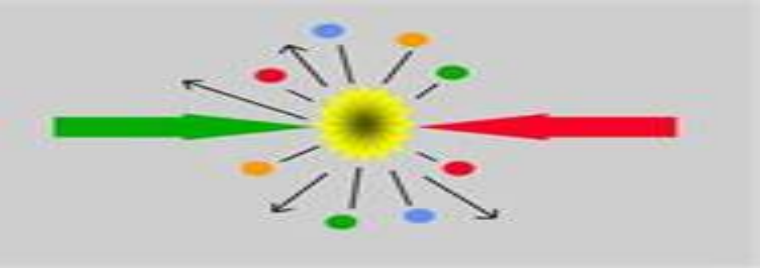
- Macroscopic objects in our world are ~neutral in terms of overall electric charge but at the most fundamental levels they consist of small bits of matter each with a well defined electrical charge: e.g.
  - Protons (charge + 1)
  - Electrons (charge -1)
  - Neutrons (charge 0)
    - Neutrons have zero electric charge and <u>alone</u> be accelerated with electromagnetic fields
  - but nuclei of atoms (with electrons removed) can be

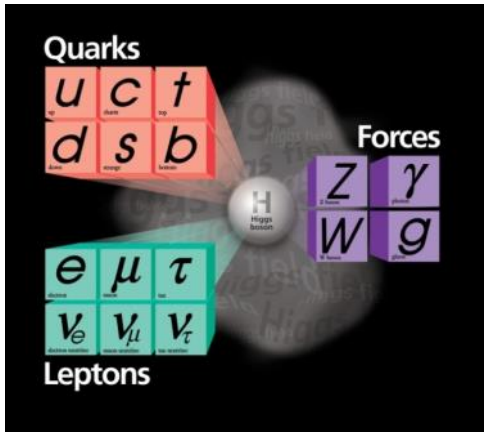
Ions
  - Helium Nucleus… Charge +2 (electrons removed)
  - Carbon Nucleus…Charge +6 (electrons removed)



Particle accelerators are energy delivery systems

- An accelerator transforms electrical energy from the power grid to many packets of energy each carried by a charged “particle”
- The energy from these particles can then be delivered in very precise ways to perform a variety of functions
- One function is for basic research (e.g High Energy Physics at Fermilab)
- Collisions create intense localized energy regions simulating conditions at the birth of the universe





- Allows scientists to explore and understand the force laws and basic building blocks of our universe

Accelerators for Discovery Science

Accelerators have transformed our understanding of the universe but these are large and complex. Most accelerators are smaller & used in Industry & Medicine

Particle accelerators good for?

- Electron beams:
  - Create intense local heating
  - Heating can be almost instantaneous
  - Melt metals or vaporize materials to creating coatings
  - Weld dissimilar and/or refractory metals
  - Rapidly drill precision holes
  - Deposit heat deeply into a material vs the surface (a flame or laser)
  - Break difficult chemical bonds to drive chemical reactions
  - Cross link polymers to improve thermal and chemical resistance of materials, heat shrink tubing and wraps
  - Modify surface vs bulk properties (e.g. hardness via rapid heating/cooling)
  - Sterilization (directly or by creating x-rays) of medical instruments
  - Insect destruction and food preservation (directly or by creating x-rays)
    - Unlike radioactive sources like Co60, or Cs, an accelerator can be switched off…
  - Environmental remediation… effective in destroying organic molecules in water, industrial waste water, pharmaceuticals, insecticides, etc

Particle accelerators good for?

- Photons (x-rays, gamma rays, Terra Hz radiation, etc) produced from electron beams
  - Deeply penetrating, non-destructive testing & inspection
  - Security Applications: cargo scanning and airport security
  - Unravel complex molecular structures (biology, new drugs)
  - Determine materials properties and crystal structures
  - Sterilization
- Proton and Neutron beams:
  - Create isotopes for medical applications
    - Including isotopes not easily made in reactors
    - Local sources for short lived isotopes for medical tests and treatments
  - Understand internal stress and materials properties, etc. (SNS)
  - Transmute one atom/isotope into another… e.g. destroy long lived nuclear waste (either directly or via an accelerator driven reactor)
- Ion Beams
  - Widely used in the semiconductor industry, also surface modification

Fermi National Accelerator Laboratory

- Dedicated to High Energy Physics Research (Discovery Science)
- Design & Operate: High Energy, High Power (MW), Accelerators
- Largest U.S. Accelerator complex, 6800 acre site, ~$380M/yr budget, 7 accelerators, 16 km of beam lines, > 2200 users, ~1700 staff
- ~ 300 accelerator scientists and engineers + 350 technical staff
- Largest collection of Accelerator experts in North America
- We build accelerators for a living!

Fermilab Accelerator Core Capabilities

Complete accelerator design, engineering, and test capability

- Accelerator Physics, beam optics design , and computer simulation
- Radio-Frequency acceleration systems
  - RF Cavities (conventional and Superconducting)
  - RF power sources
- Magnets
  - Conventional and superconducting
  - DC and pulsed
  - Power supplies and controls
- Beam instrumentation, UHV vacuum and beam control systems
- High power targets
- State-of-the-art detectors and electronic DAQ systems
- Advanced computing & network capability
  - Big data sets (storage & analysis)
  - Advanced software
- ES&H, and safety systems for accelerator commissioning / test

Fermilab Accelerator Infrastructure

- In support of our Science Mission we develop accelerators that constantly push the state-of-the-art
- Already in partnership with universities-labs-industry
  - Purchase industry made components with demanding specifications
  - Integrate components and test them, assemble large complete accelerators on site
- **Our mission requires us to build and maintain literally hundreds of millions of dollars worth of sophisticated accelerator infrastructure.**
- Beam test facilities
- Accelerator component development and test facilities
  - Specialized fabrication facilities
  - Magnets and RF cavities test infrastructure (warm and superconducting)
  - RF power sources and electronics test stands
  - Large cryogenic systems
- **Access to lab infrastructure can enable partnerships to create new applications and the specialized accelerators to drive them**
- **Tour and speed date preview:**

Accelerator Physics and Simulation

Accelerator Simulation

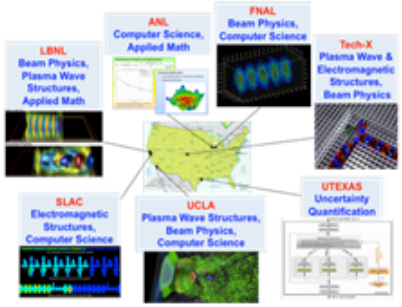
Understanding the dynamics of many bunches of 10^{11} charged particles inside of a metal vacuum chamber is a complicated problem that can only be handled with numerical simulations. Detailed simulations can help us optimize existing accelerators as well as design new machines in furtherance of Fermilab's mission and our responsibilities as stewards of accelerator knowledge and capabilities.

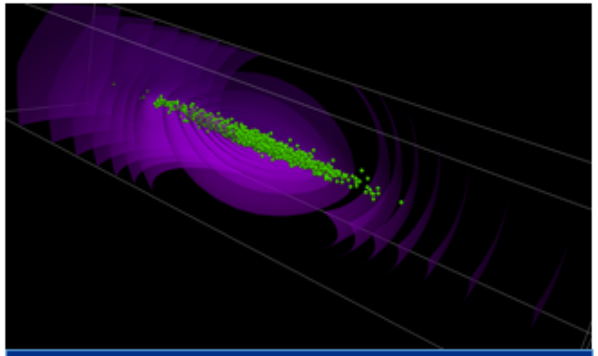
Synergia

Synergia is a Fermilab developed accelerator simulation package that specializes in detailed simulations of collective effects of *space charge* and *wakefields*. Synergia simulations can be small enough to run on a laptop or large enough to require supercomputing technology.

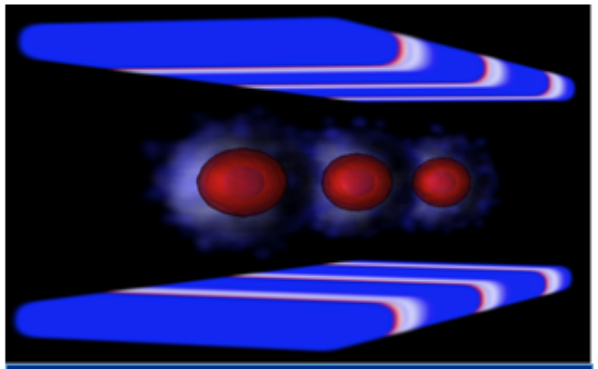
ComPASS Collaboration

The ComPASS collaboration led by Fermilab is a multi-institution collaboration combining the best computer science, applied mathematics and accelerator physics to the problem of accelerator simulations. ComPASS is funded by the DOE SciDAC program.

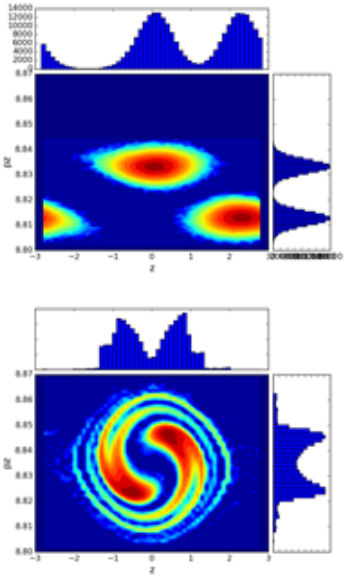




Space charge is the electromagnetic repulsion among the particles in a beam bunch. Its effects increase as intensity increases. Pictured above is a self-consistent Synergia space charge simulation. The green particles generate the purple fields which in-turn affect the motion of the particles.



Wakefields are electromagnetic fields generated in accelerator structures by passing beams. Pictured above is a self-consistent Synergia simulation of three bunches of particles producing wakefields in the surrounding beam pipe which in turn affects the motion of the particles.



Fermilab uses a technique called *slip stacking* to combine pairs of bunches in order to create a more intense beam. The flexibility of Synergia allows us to simulate the detailed beam manipulation that occurs during slip stacking. Synergia simulations of slip stacking, shown to the left, allow us to investigate potential problems that may arise during the production of the higher intensities as well as mitigation strategies to ensure success of the future Fermilab program.

Synergia runs on a variety of platforms from desktop/laptops to Linux clusters to supercomputers. Pictured are: a MacBook, the Wilson Cluster at Fermilab, the Mira supercomputer at Argonne National Laboratory, the Edison supercomputer at National Energy Research Scientific Computing Center.

Beam Test Facilities

ASTA / IOTA: Beam Test Facility

The Advanced Superconducting Test Accelerator accelerates electrons providing beams of 50 -300 MeV

Pulsed operation 1 ms pulses 1-5 Hz
Photo injector = small beam emittance
Test areas for instrumentation and new components
New concepts: Integrable Optics Test Accelerator

Already many Industry-lab-university partnerships

Top: 50 MeV injector and experimental area
Bottom: 1.3 GHz SRF cryomodule

Neutron Irradiation Facility

66 MeV Neutrons
Test radiation hard electronics

Precise neutron dose delivery

FTBF

Fermilab Test Beam Facility
Detector Development

20 GeV: Protons
66 - 8 GeV: Pions
32 - 1 GeV: Pions, e, K, muons
~.2-1 GeV Tertiary Beams

MuCool Test Area

400MeV Proton beam line from linac

5 Tesla Solenoid, 805 MHz copper cavity
200 MHz copper cavity

RF Power test stands
- 805 MHz,
- 201 MHz

Top: MuCool Beam line
Bottom left: 805 MHz cavity in 5 T SC magnet
Bottom right: 201 MHz cavity

Superconducting and Conventional Magnets

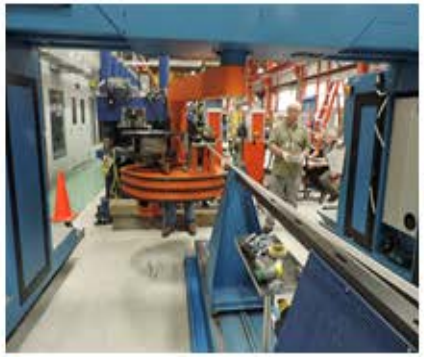
Super Conducting Magnet Development

Fermilab has been at the forefront of superconducting magnet manufacturing for particle accelerators since its inception, beginning with the Tevatron and continuing through the SSC, the LHC, and many others. Capabilities include heat treatment and testing of conductor, as well as manufacturing and testing of cable and complete magnets.

Critical current density of superconductor is measured at various temperatures and external magnetic fields. The facility for heat treating and testing strand is shown at right.

Four magnetic cryostats with up to 15T / 17 T background field, and with cold apertures between 64 mm and 147 mm are connected to new vent and vacuum systems.

Superconducting Cable is manufactured in Technical Division. The Fermilab cabling machine is shown below. NbTi or Nb_3Sn cable of up to 42 strands are used on various superconducting magnet projects, supporting the R&D needs of Fermilab, CERN and other labs. Cable of round, rectangular or trapezoidal shapes are manufactured with cross sectional accuracies of +/- 6 microns. To the right are spools of strand and a section of completed cable.



Dipole

Quadrupole

The cable is insulated, then wound into a coil. Each turn must be placed precisely into position to achieve the proper magnetic field shape. Coils may be wound into various configurations, but are usually either dipole (to bend the beam) or quadrupole (to focus the beam). The winding machine for the LHC upgrade is being commissioned above. In the current configuration, coils can be wound up to 6.5 meters long, but it can be configured to wind coils over 16 meters in length.

Once a Nb_3Sn coil is produced, it must be heat treated to give the coil its superconducting properties. This is done in a large "reaction oven" as shown above. The coil is heated in steps to various temperatures up to 650 degrees Celsius for a period of nearly 2 weeks, then removed from the oven and impregnated with epoxy.

Completed magnets, with or without a cryostat, are tested at the TD Magnet Test Facility. Magnets with a cryostat are tested horizontally, those without are tested in a re-useable vertical helium vessel. VMTF is the largest of several test stands, and is underground.

Vertical Magnet Test Facility

Large SC Magnet R&D
{ <0.625m OD, <3.7m long }

Temperature 1.9 K to 4.6 K
Current up to 30 kA

Quench Protection
{ dump resistor, heaters }

Quench Characterization
{ ~100 voltage taps
isolation amplifiers
fast data loggers }

Splice resistance
AC Loss measurement
Magnetic measurements
Warm bore tubes

Photos:
a) Magnet hookup to top plate assembly
b) Insertion into 6m deep helium cryostat
c) Magnetic measurement cart with rotating coil drive tower mounted over top plate

Superconducting Radio Frequency Cavity Surface Processing Infrastructure

EP tool at ANL/FNAL facility

Similar EP tool at FNAL

High Pressure Rinse

EP tool for ¼ wave HWR, and 650 MHz at ANL/FNAL Facility

One of two large ultra-clean vacuum ovens

FNAL Clean Rooms

Several Class (10, 100) spaces

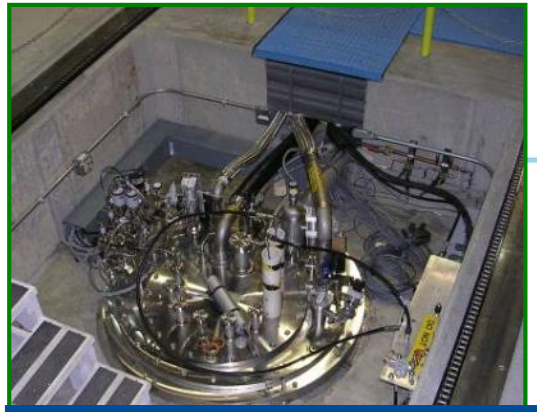
MP9 Clean Room 2500 ft^2

CMTF Clean Room 900 ft^2

SRF Cryomodule Assembly

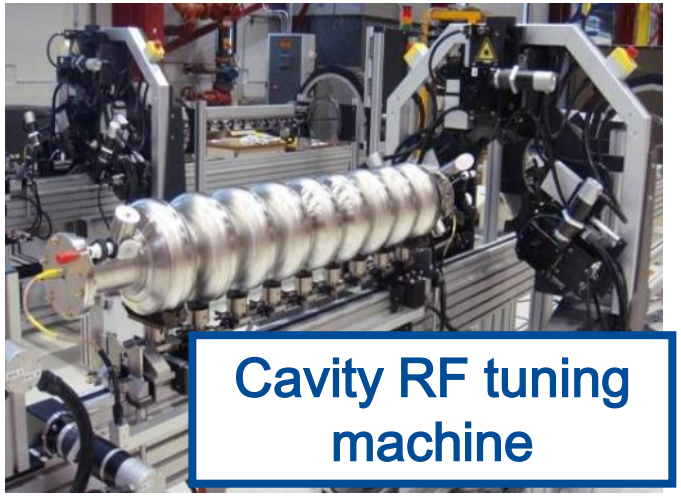
Ultrasonic cleaners

SRF Cavity Test Infrastructure



VTS 1 of 3 Dewars

VTS



Cavity RF tuning machine

HTS dressed cavities

STC

A 325MH spoke cavity that will be part of a PIP-II prototype cryomodule is being installed in the STC cryostat on the left. On the right the STC cryostat is closed up and being cooled down in preparation for RF testing of the cavity..

Cryogenics and Heavy Assembly Capability

500W 2 K Cryo Plant

CM Final Assembly

Measurement and QC Equipment

Coordinate Measurement Machines

X-ray florescence analyzer for materials composition

Radio Frequency (RF) Capabilities at Fermilab

High Level RF

The Fermilab accelerator complex utilizes a wide range of RF power sources and transmission lines with frequencies of operation from a few MHz to 3.9 GHz,

pulsed and CW systems, power ranging from Watts to MWatts.

Depicted are several examples of operational systems used throughout the accelerator complex.

Top left: 2.5 MW 325 MHz klystron 3 msec @ 10 Hz, Top right: 325 MHz @ 10 kW CW, Bottom: Inductive Output Tube (IOT) amplifiers operate in CW or pulsed mode 400-800 MHz & 1.3 GHZ @ 30 kW

RF Systems

Radio Frequencies are used extensively in telecommunications, medical scanners, electronic sensors, advanced manufacturing systems, and homeland security. RF systems for accelerators consist of low level RF, high level RF, power distribution, and cavities. Brought together, these systems allow for beam acceleration and manipulation with novel techniques. These same advances have potential in industrial applications.

LLRF circuitry combines both analog and digital hardware with DSP and FPGAs for powerful computational capabilities.
Features: 16 ch ADC,8 ch DAC, Hi speed PCIe data bus,

Low Level RF

Sophisticated state of the art LLRF controls the RF systems amplitude and phase by means of feed-forward and feedback. Digital techniques allow real time RF manipulation that was unimaginable a decade ago.

Experience with copper, aluminum, and niobium cavities.

Left: 201 MHz Cavity for Muon Ionization Cooling Experiment (MICE)

Right: 2.45 GHz single cell SRF cavity driven by an injection locked magnetron.

Below: clean room cavity tuning

Cavities and Kickers

Structures to support large voltage gradients for acceleration, beam manipulation, bunching, and diverting kickers. Extensive experience with a variety of CAD modeling software for development of such structures. Fabrication facilities in house and expert outside vendors.

Broadband Kickers for Beam Deflection. 1GHz Bandwidth plus/minus 250 Volts

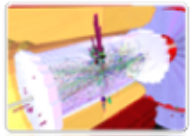
Fermilab Scientific Computing Capabilities

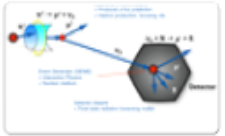
Compute Hardware, Software, Networks, Expertise

Detector & Physics Simulation

Dr. Daniel Elvira
Head of Scientific Computing Simulation Department

Large-scale simulation of detectors, computer-generated event data that behaves exactly as real data, and computational models of the physics processes, are crucial parts of designing and operating detection instruments. Fermilab contributes to the development and support of Pythia, for collider physics, Genie, for neutrino physics and Geant4, for modeling detectors. Geant4 is in use also for space science, nuclear, and medical physics. Simulation software is utilized to understand detectors and data from small to large scales. There is ongoing R&D to adapt the toolkits to use modern computer architectures, e.g. general purpose GPU and Intel-Phi, for fine granularity parallelism in multithreaded simulation applications.





Big Data Analysis R&D

Dr. Andrew Norman
Head of Scientific Data Management Applications

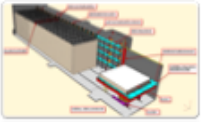
"Big Data" techniques, where data is not moved to the computational resource but the computation is moved to the data, are a promising avenue to reduce the time to physics results. These techniques remove the lines between the different analysis tasks, allowing efficient selection of portions of event data, or "skims" directly on the entire set of files (dataset). Key is striping data storage across sites and running portions of the selection codes where the data resides.

We are now exploring such techniques for both the CMS and the NoVA neutrino experiments to provide easy selection and understanding of interesting phenomena from 10s of terabytes of disk-resident event data and using globally "federated" disk stores of the preliminary processed data.

Data Detection & Acquisition

Dr. Kurt Biery
Head of Real Time Systems and Engineering Department

Artdaq is a framework for developing data acquisition systems used by neutrino, muon, and dark matter experiments. It is an integrated system with extensions for each experiment across multiple performance scales. Artdaq interfaces to many of the custom electronics and readout systems developed both by the experiments and Fermilab engineering.
A research (LDRD) project is underway to provide a low-cost, scalable system architecture based on commercial technology developed for the "Internet of Things." Off the Shelf DAQ (OTSDaq) connects intelligent front-end digitizers directly to a standard network without additional layers of custom readout electronics. The goal is to provide an off-the-shelf solution that provides immediate hardware, firmware, and software DAQ functions. The system will scale from a few MB/s to hundreds of GB/s using inexpensive commodity networking equipment and interface modules.



Distributed Data Processing

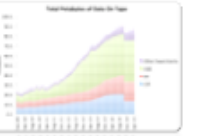
Dr. Robert Illingworth
Head of Serial Analysis with MetaData (SAM) Project

Data distribution tools ensure physics data is sent to and received from remote universities and collaborators over the Internet. The Serial Analysis with MetaData (SAM) system is used by multiple experiments to keep track of millions of files together with their parentage, contents and types. SAM includes project-specific meta-data in addition to supporting data storage and analysis sites worldwide.
Fermilab is a leading contributor to the Open Science Grid multi-disciplinary community of computing and storage owners, software providers and scientific researchers.

Data Archiving & Preservation

Dr. Gene Oleynik
Head Data Management and Storage Department

Fermilab currently stores more than 50 PB of data on tape, and supports the software and systems that provide high throughput multi-stream storage and retrieval of the files, sharing of tape drives, and intelligent placement of the files.
The Active Archive Facility (AAF) is a high performance active (aka nearline) service offered to researchers through the Strategic Partnership Project (SPP). The AAF has a capacity of tens of Petabytes and multiple Gigabytes per second of aggregate bandwidth and is providing long term preservation and custodial care along with high-performance retrieval. Data is protected through policies and procedures, together with periodic read validation, as well as on-request replication of files for redundancy.



Software Frameworks

Dr. Jim Kowalkowski
SCU Assistant Head for R&D & Architecture

art, a generalizable data analysis and processing framework based originally on the CMSSW CMS experiment framework, is now in use by multiple experiments at Fermilab and elsewhere. Many scientists analyze the data together to produce physics results and discoveries. Shared software frameworks provide common components of an application (such as data input and output, including external common plotting and histogramming libraries, and error message detection and reporting) and the means to integrate experiment/project specific physics algorithms. Common frameworks also encourage documentation and training that can be shared by all. Fermilab teams are extending these frameworks for with new computer architectures.
The software code repositories, build-and-release systems, are supported as part of the broader software ecosystem to give the physicists easy to learn and use end-to-end systems.

Illinois Accelerator Research Center (IARC)

Mission

Partner with industry to exploit technology developed in the pursuit of science to create the next generation of industrial accelerators, products, and new applications.

Vision

IARC will be the preeminent national enabler of accelerator based products and services serving as the seed for industry growth.

IARC: An unusual DOE-State of Illinois Partnership

- Facility construction is joint funded
  - $ 20 M grant from State of Illinois DCEO
  - $ 13 M of DOE funding for design, site prep, and outfitting
  - $ Refurbished $ 38 M Heavy Assembly building

Thanks!

New office space and meeting rooms
48,000 square feet (lobby view)

A new facility under construction
first occupants next month

Dedicated to Lab-Industry-University Partnerships on Accelerator Technology

- **Reused bldg from Tevatron (42,000 sq ft)**
- **50 T crane; 10 T crane, Machine shop**
- **Deep pit for shielding accelerators**
- **1.5 MW of installed electrical power**
- **2.0 MW of industrial, LCW, and chilled water**
- **600 W @ 4 K cryogenic refrigerator**
- **Fully permitted to test new accelerators**
- **Irradiation facility planned**

Summary

- Accelerators are very useful tools!
- In pursuit of its basic science Mission for DOE, Fermilab designs and builds large state-of-the-art accelerators
  - We have extensive accelerator capabilities and infrastructure
- We plan to make these capabilities and infrastructure accessible for industry-lab-university partnerships through the Illinois Accelerator Research Center
  - Goal: Develop new accelerator capabilities and applications, create entire new industries, and high tech jobs
- The DOE Accelerator Stewardship Test Facility Pilot Program is a new program that will promote such partnerships
- We look forward to showing you <u>our</u> capabilities and learning how they might help solve <u>your</u> problems.
- Thanks for coming!