CONTROL ROOM ACCELERATOR PHYSICS

Lecture 1

Overview of Accelerators and Accelerator Control

Outline

1. Basic Operation
   1. We present the basic operation for accelerators.
   2. Provides introduction to tasks, tools, and diagnostic available to controls personnel.
2. Accelerator Principles
   1. Basic Principles
   2. Accelerating Structures
   3. Particle Beam Optics
3. Accelerator Control
4. Accelerator Simulation
5. Summary

SUBATOMIC PARTICLES

Subatomic particles fall into two major groups: the elementary particles and the hadrons. An **elementary particle** is not composed of any smaller particles and therefore represents the most fundamental form of matter. A **hadron** is composed of elementary particles called **quarks.** This table contains the most common subatomic particles, including the major constituents of the **atom**—the **electron** (an elementary particle), and the **proton** and the **neutron** (hadrons).

Explanation of column headings:
PARTICLE SYMBOL A superscript indicates charge.
ANTIPARTICLE SYMBOL Typically the same as the particle symbol but often with a bar above it.
COMPOSITION The combination of quarks that make up the hadron. Some hadrons are members of multiplets that differ in isospin and their compositions are best described by using mathematical expressions.
MASS Expressed as a multiple of an electron's mass, 9.1066×10^{-28}g or 0.511 MeV.
ELECTRIC CHARGE Expressed as a multiple of an electron's charge, -1.602×10^{-19} coulomb. The antiparticle has a charge opposite that of its corresponding particle, except when both are neutral.
LIFETIME The average time in seconds that the particle exists. "Stable" means that the particle has no known mode of decay.

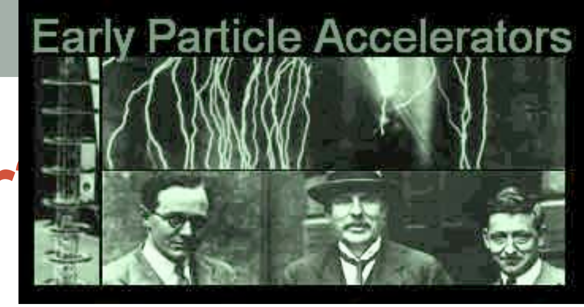
ELEMENTARY PARTICLES

Family Name	Particle Name	Particle Symbol	Antiparticle Symbol	Mass	Electric Charge	Lifetime in Seconds
Gauge Bosons: classon	photon	γ	γ	0	0	stable
	graviton	g	g	0	0	stable
	gluon	g	g	0	0	?
Gauge Bosons: intermediate vector boson	W boson	W^-	W^+	157,000	−1	$>3.2 \times 10^{-25}$
	Z boson	Z	Z	178,000	0	$>2.6 \times 10^{-25}$
lepton	electron	e or e^-	e^+	1	−1	stable
	electron neutrino	ν_e	$\bar{\nu}_e$	$<3 \times 10^{-5}$	0	$>1.5 \times 10^{8}$ (stable?)
	muon	μ or μ^-	μ^+	207	−1	2.2×10^{-6}
	muon neutrino	ν_μ	$\bar{\nu}_\mu$	<0.33	0	$>8 \times 10^{6}$ (stable?)
	tau	τ or τ^-	τ^+	3,480	−1	3.0×10^{-13}
	tau neutrino	ν_τ	$\bar{\nu}_\tau$	<59	0	$>8 \times 10^{6}$ (stable?)
quark	up	u	$\bar{u}$	10	+2/3	stable
	down	d	$\bar{d}$	20	−1/3	stable
	charm	c	$\bar{c}$	2,935	+2/3	?
	strange	s	$\bar{s}$	391	−1/3	?
	top	t	$\bar{t}$	352,000	+2/3	?
	bottom	b	$\bar{b}$	9,200	−1/3	?

HADRONS

Family Name	Particle Name	Particle Symbol	Antiparticle Symbol	Composition	Mass	Electric Charge	Lifetime in Seconds
baryon	proton	p or p^+	$\bar{p}$	uud	1,836	+1	stable
	neutron	n or n^0	$\bar{n}$	udd	1,839	0	887
	lambda	Λ^0	$\bar{\Lambda}^0$	uds	2,183	0	2.6×10^{-10}
	lambda-c	Λ^+_c	Λ^-_c	udc	4,471	+1	2.1×10^{-13}
	lambda-b	Λ^0_b	$\bar{\Lambda}^0_b$	udb	11,000	0	1.1×10^{-12}
	sigma	Σ^+	$\bar{\Sigma}^+$	uus	2,328	+1	0.8×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	$\frac{(ud \pm du)s}{\sqrt{2}}$	2,334	0	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^-$	dds	2,343	−1	1.5×10^{-10}
	xi	Ξ^0	$\bar{\Xi}^0$	uss	2,573	0	2.9×10^{-10}
		Ξ^-	$\bar{\Xi}^+$	dss	2,585	−1	1.6×10^{-10}
	xi-c	Ξ^0_c	$\bar{\Xi}^0_c$	dsc	4,834	0	9.8×10^{-14}
		Ξ^+_c	$\bar{\Xi}^-_c$	usc	4,826	+1	3.5×10^{-13}
	omega	Ω^-	Ω^+	sss	3,272	−1	0.8×10^{-10}
	omega-c	Ω^0_c	$\bar{\Omega}^0_c$	ssc	5,292	0	6.4×10^{-14}
meson	pion	π^+	π^-	$u\bar{d}$	273	+1	2.6×10^{-8}
		π^0	π^0	$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}$	264	0	8.4×10^{-17}
	kaon*	K^+	K^-	$u\bar{s}$	966	+1	1.2×10^{-8}
		K^0	$\bar{K}^0$	$d\bar{s}$	974	0	8.9×10^{-11} 5.2×10^{-8}
	J/psi	J or Ψ	J or Ψ	$c\bar{c}$	6,060	0	1.0×10^{-20}
	omega	ω	ω	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,532	0	6.6×10^{-23}
	eta	η	η	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,071	0	3.5×10^{-22}
	eta-c	η_c	η_c	$c\bar{c}$	5,832	0	3.1×10^{-22}
	B	B^0	$\bar{B}^0$	$d\bar{b}$	10,331	0	1.6×10^{-12}
		B^+	B^-	$u\bar{b}$	10,331	+1	1.6×10^{-12}
	B-s	B^0_s	$\bar{B}^0_s$	$s\bar{b}$	10,507	0	1.6×10^{-12}
	D	D_0	$\bar{D}_0$	$c\bar{u}$	3,649	0	4.2×10^{-13}
		D^+	D^-	$c\bar{d}$	3,658	+1	1.1×10^{-12}
	D-s	D^+_s	D^-_s	$c\bar{s}$	3,852	+1	4.7×10^{-13}
	chi	χ^0_c	χ^0_c	$c\bar{c}$	6,687	0	3.0×10^{-22}
	psi	Ψ^0_c	Ψ^0_c	$c\bar{c}$	7,213	0	1.5×10^{-20}
	upsilon	Υ	Υ	$b\bar{b}$	18,513	0	8.0×10^{-20}

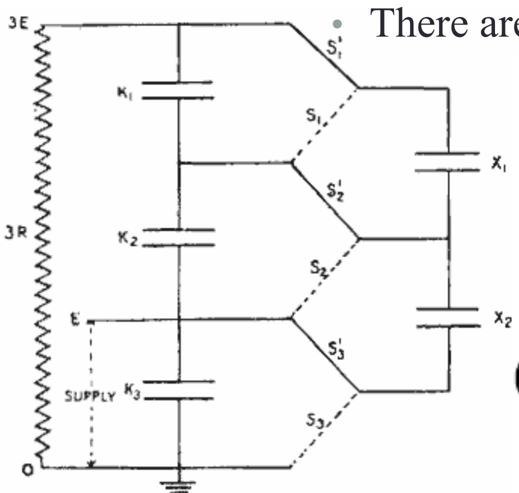
*The neutral kaon is composed of two particles; the average lifetime of each particle is given.

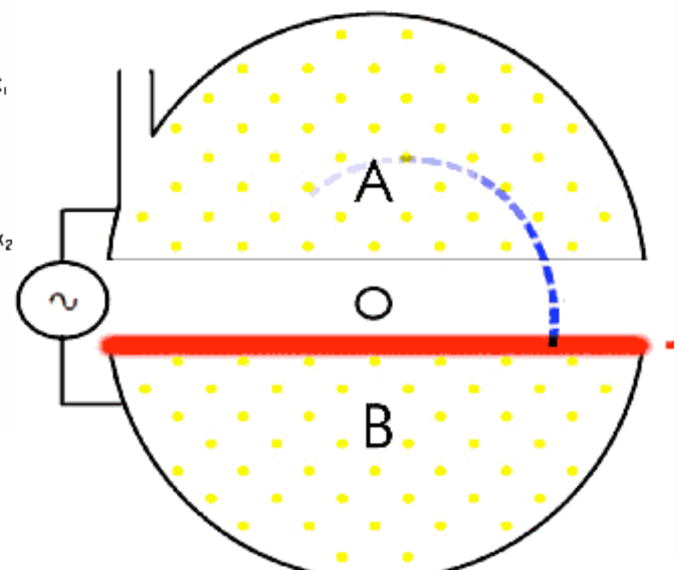


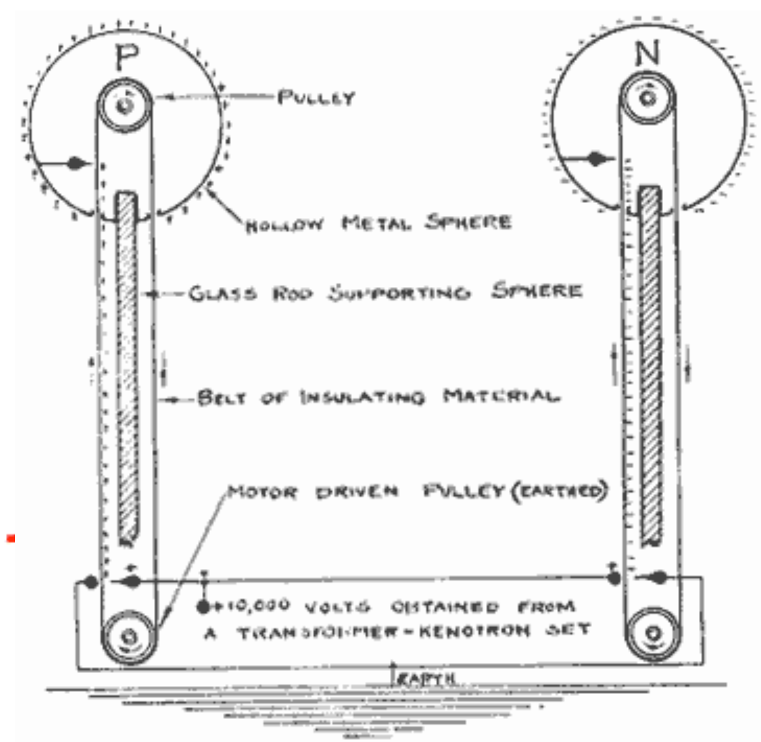
1. What is an Accelerator?

An accelerator is a machine which accelerates charged particles to very high energy.

- There are many structure types
  - Provide differing performance regimes
  - Two basic varieties are *linear* and *circular*
- There are many particles flavors
  - Leptons, Hadrons, Ions
- There are many applications







1. Accelerator View: Satellite

It can be big!

1.1 Motivation – Why Accelerators?

- Accelerators are big, expensive, and high maintenance machines. Why build them?

"..who would not want to live in a country that built such machines…"

Leon Lederman
Address to U.S. Congressional concerning the construction of the Tevatron at Fermilab, Batavia, IL

- Some Accelerator Applications
  - High Energy Physics (HEP)
    "How does the universe work?" more energy = more exotic particle
    - Neutrino physics
    - Neutron physics
  - Accelerator Driven Sources (ADS)
  - Medical applications (e.g., proton therapy)
  - Neutron sources
  - Light sources

1.2 Some Accelerator Facilities

USA

- Fermilab, Batavia IL
- Argonne, Argonne, IL
- SLAC, Paolo Alto, CA
- Lawerence-Berkeley, Berkeley
- Brookhaven, Long Island
- University of Indiana
- Michigan State University
- University of Maryland
- MIT, Cambridge, MA
- Cornell University, Ithaca, NY

World

- CERN, Geneva
- KEK, Tsukuba, Japan
- PSI, Villigen, Switzerland
- DESY, Hamburg
- GSI, Darmstadt
- CEA, Saclay, France
- Rutherford-Appleton, Oxfordshire
- Shanghai Light Source
- POSTECH, Pohang, South Korea
- Australian Synchrotron, Melbourne

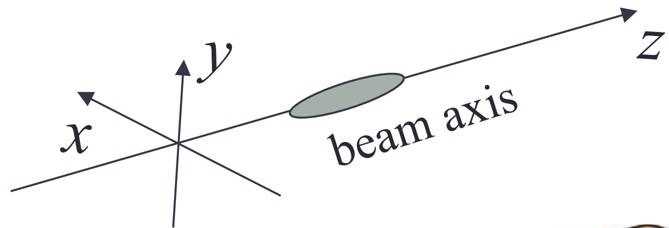
2.1 Basic Accelerator Principles

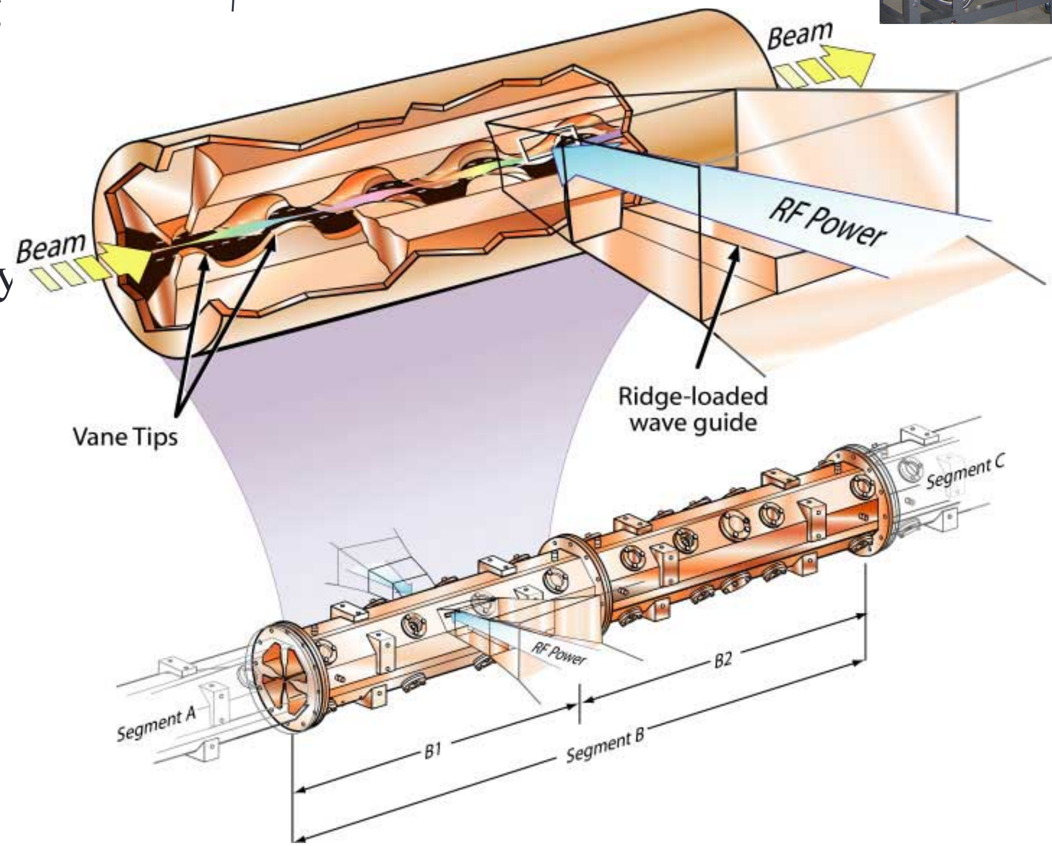
Three basic ingredients

1. Particle Beam
   1. Ensemble of self-interacting particles

2. Accelerating structure
   1. Resonant RF cavity specially shaped to provide strong fields on beam axis

3. RF Power
   1. RF energy converted to particle kinetic energy





2.1 Basic Accelerator Principles

Mechanics

- Lorentz force law in an EM field

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

$\mathbf{F}$ – force on particle
q – particle charge
$\mathbf{v}$ – particle velocity
$\mathbf{E}$ – electric field
$\mathbf{B}$ – magnetic field

- Energy Gain ΔW from an EM field (work done on particle by field)

$$\Delta W = \int \mathbf{F} \cdot d\mathbf{r}$$

$$= q\int \mathbf{E} \cdot d\mathbf{r} + q\int \frac{d\mathbf{r} \times \mathbf{B} \cdot d\mathbf{r}}{dt}$$

$$= q\int \mathbf{E} \cdot d\mathbf{r}$$

(the second term is marked with an arrow: 0)

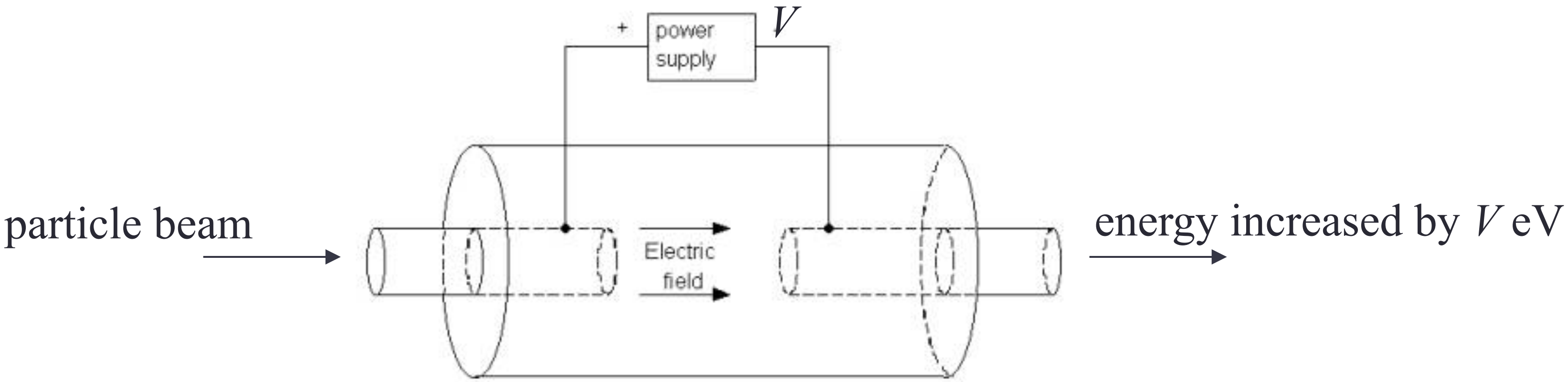
Only electric fields in the direction of propagation affect **energy gain**

- Accelerating structures create strong electric fields in the direction of propagation

2.2 Basic Accelerator Structures

Van der Graff Acceleration

- Simple static acceleration
  - Charged parallel plate capacitor with beam aperture
  - Particle falls through a potential V

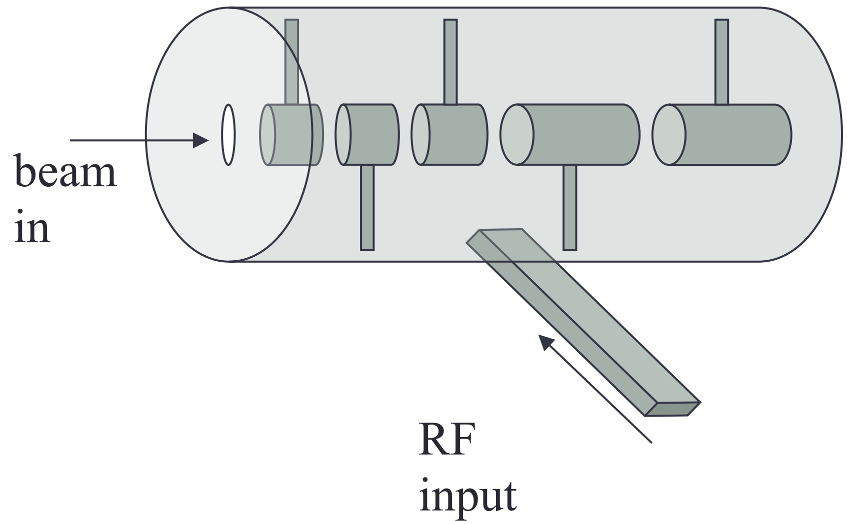


- So why use RF?
  - The SNS linac would require a stack of plates with a total **floating** voltage of 1,000 MV (about 667 million D-cell batteries)

2.2 Accelerating Structures
The Drift Tube Linac (DTL)

- DTL invented by Luis Alvarez in 1946 at Berkeley
  - Pillbox resonant cavity with grounded shielding tubes

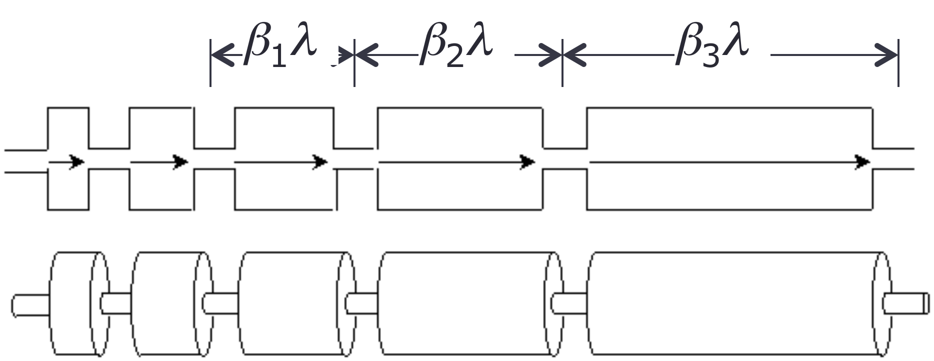
- Beam
  - Beam injected after fields established
  - "Drift" tubes isolate beam while RF fields change sign



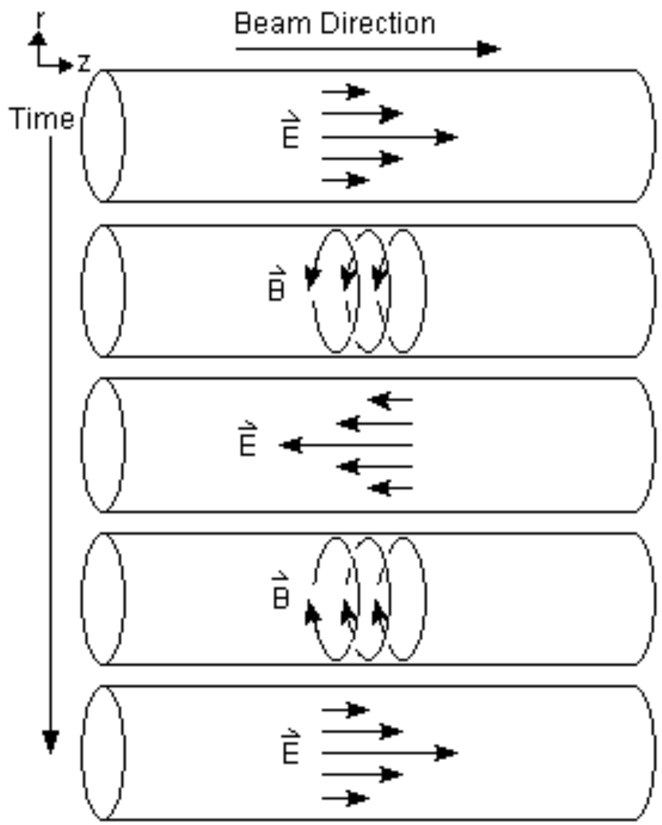
- RF Drive
  - Use fundamental TM_{010} mode (longitudinal E field)

2.2 Accelerating Structures
Drift Tube Linac (cont.)

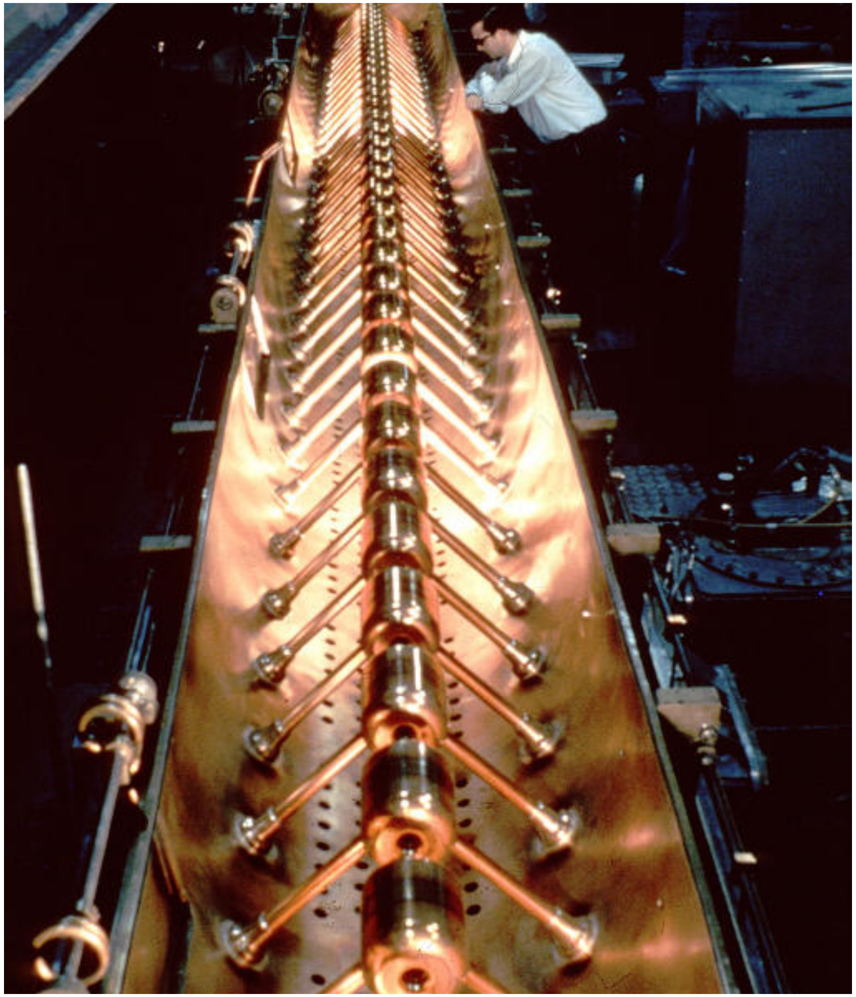
- Without drift tubes no net acceleration could occur
- Drift tube shield particle from neg. RF
  - Length = $\beta\lambda$, $\beta = v/c$
  - Must get longer as particle accelerates



Constant Frequency with an Increasing Acceleration Gap Length



2.2 Examples of Actual DTL Tanks



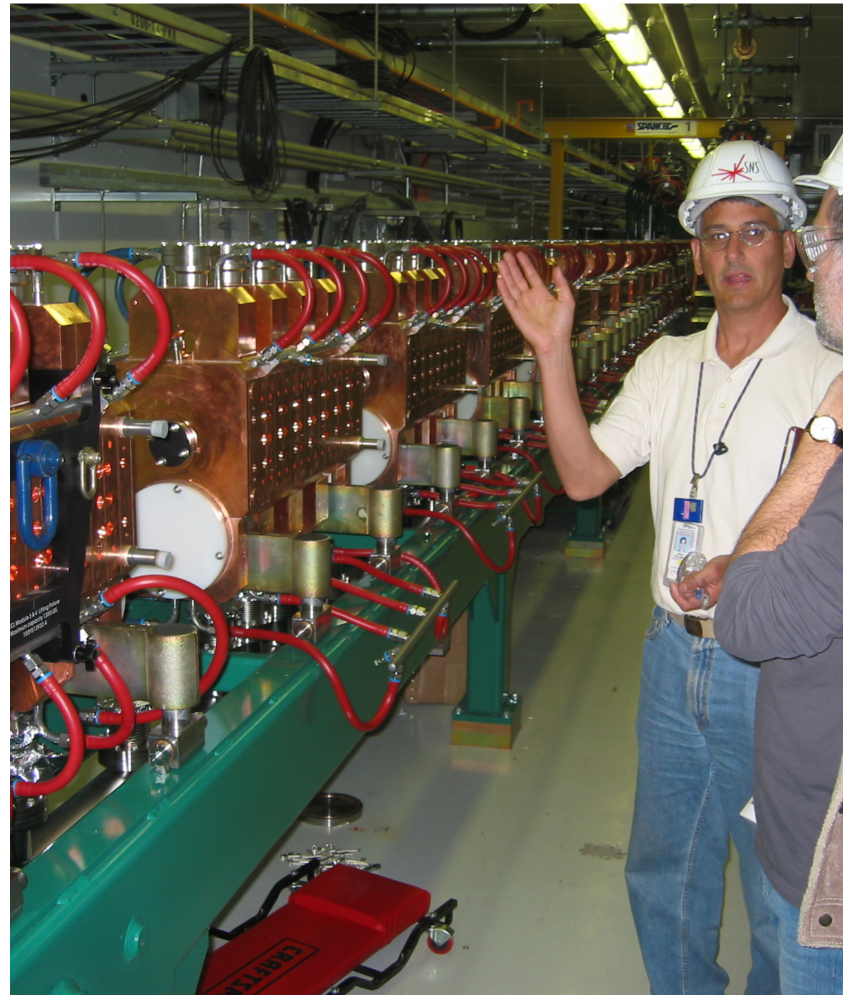
CERN DTL

Fermilab DTL Tank #2

2.2 Accelerating Structures

SNS Facility - DTL Tanks and CCDTL Tanks

SNS DTL tanks 6 pre-install



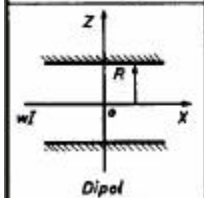
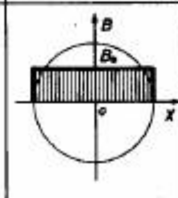
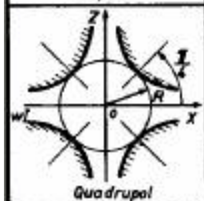
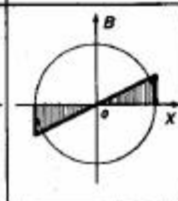
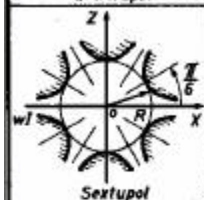
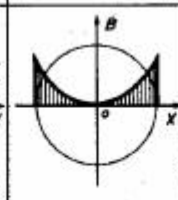
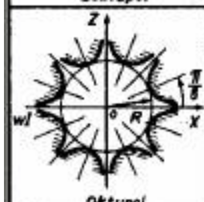
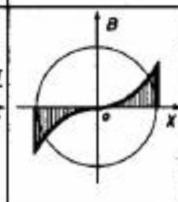
SNS CCDTL tanks installed in tunnel

2.3 Particle Beam Optics

Beam Optics with Mass

- We employ a full complement of multi-pole magnets for
  - Bending (dipole)
  - Steering (dipole)
  - Focusing/Defocusing (quadrupole)
  - Chromatic tuning (sextupole)

- Note that there are two categories
  - Single particle dynamics – beam position
  - Multiple particle dynamics – beam shape

Pole shape	Field	Pole,analyt.	B_x	wI
		$z=\pm R$	$a_1=B_0$	$\frac{2}{\mu_0}B_0R$
		$xz=\pm\frac{R^2}{2}$	$a_2x=gx$	$\frac{1}{\mu_0}gR^2$
		$z(x^2-\frac{z^2}{3})=\pm\frac{R^3}{3}$	$a_3(x^2-z^2)$	$\frac{2}{3\mu_0}a_3R^3$
		$xz(x^2-z^2)=\pm\frac{R^4}{4}$	$a_4x(x^2-3z^2)$	$\frac{1}{2\mu_0}a_4R^4$

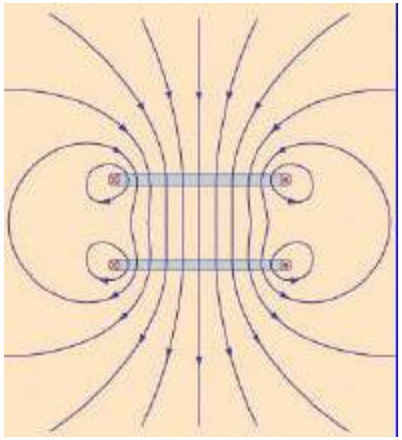
“Catalogue” of beamline optical devices

2.3 Particle Beam Optics Dipole Magnets

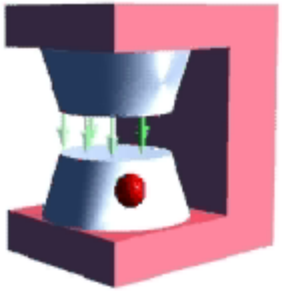
- Dipole magnets provide
  - Bending of entire beamline
  - Focusing beam within beamline

- They also cause dispersion

  Particles of different energies are bend at different angles
  - Analogous to a light prism
    - Mass spectrograph
    - Beam degradation (sextupole correction)



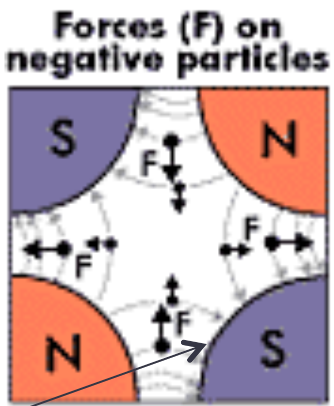
Dipole field of a Helmholtz coil



2.3 Particle Beam Optics
Quadrupole Magnets

- To maintain beam containment transverse forces must be applied

- Magnetic **quadrupole** "lenses" provide t transverse forces



Note for linear fields: pole face boundaries are $x^2 - y^2 = R^2$

$$\mathbf{F} = q\mathbf{v}\times\mathbf{B} \quad \text{or} \quad \begin{aligned} F_x &= qvB_y \\ F_y &= -qvB_x \end{aligned}$$

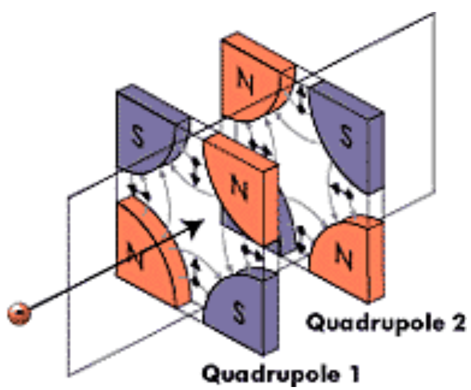
Quadrupole lenses are always focusing in one transverse plane but **defocusing** in the other

2.3 Particle Beam Optics

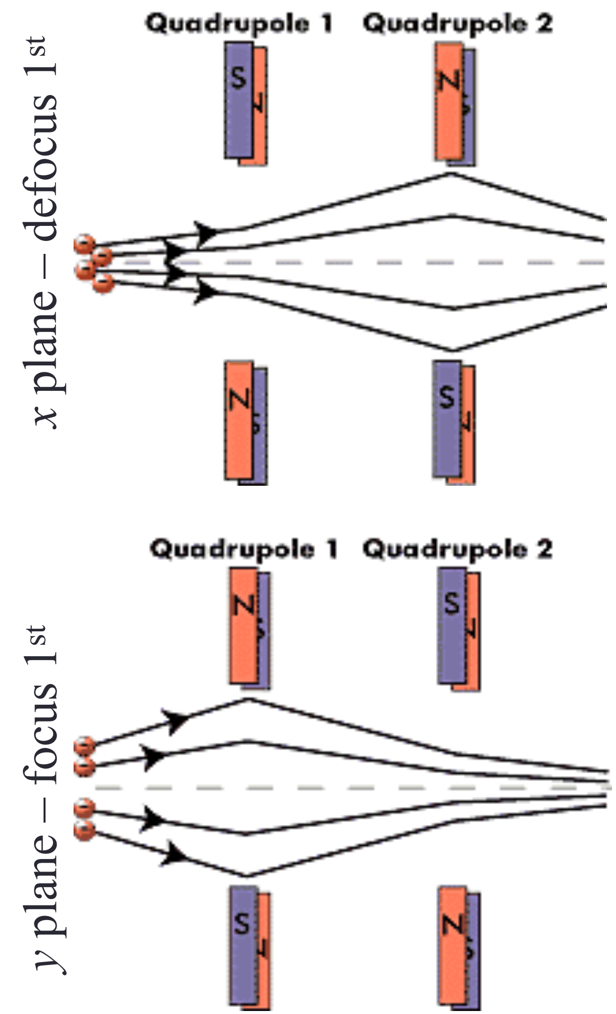
Transverse Focusing (cont.)

- We can achieve a net (strong) focusing by pairing quadrupoles with opposite polarities

  Known as
  - FODO arrangement
    (Focusing, Zero, Defocusing, Zero)
  - Alternating Gradient (AG) focusing



Two quadrupoles in a FODO arrangement



2.3 Particle Beam Optics
Focusing and Bending Magnets

SNS ring bending dipole

SNS ring quadrupole magnet

3 Accelerator Control

Accelerator Control Problems (Rings, Optics, etc.)

- Steering
  - Maintain "Golden" orbit
  - Collision interaction region (Simulation)
- Focusing (beam containment)
  - Chromatic aberrations – Off momentum particle focused differently
  - Envelope matching between accelerator sections – Envelope Oscillations
- Two-stream instability
  - Free electrons in beam pipe act as plasma stream (Simulation)
- Multiple-Impacting (Multipacting)
  - Electron impacts with beam pipe creates cascade of secondary emissions (Simulation)

3. Accelerator Control

What aspects are unique to accelerators?

- Extremely tight requirements
  - Must steer to **μm** tolerance over **kilometers** of beamline
- Atypical control system
  - "Deadbeat" systems – no continuous dynamics, finite step solvable
  - Because $v \sim c$ we cannot control individual beam pulses (no "state")
  - Coupled spatially, upstream actions affects everything downstream
- Noise is an integral part of the system
  - Ground motion, alignment errors, instrument noise, etc.
  - Trains, waves, tides, all affect machine performance

3. Accelerator Control

Control Systems and Controls Theory

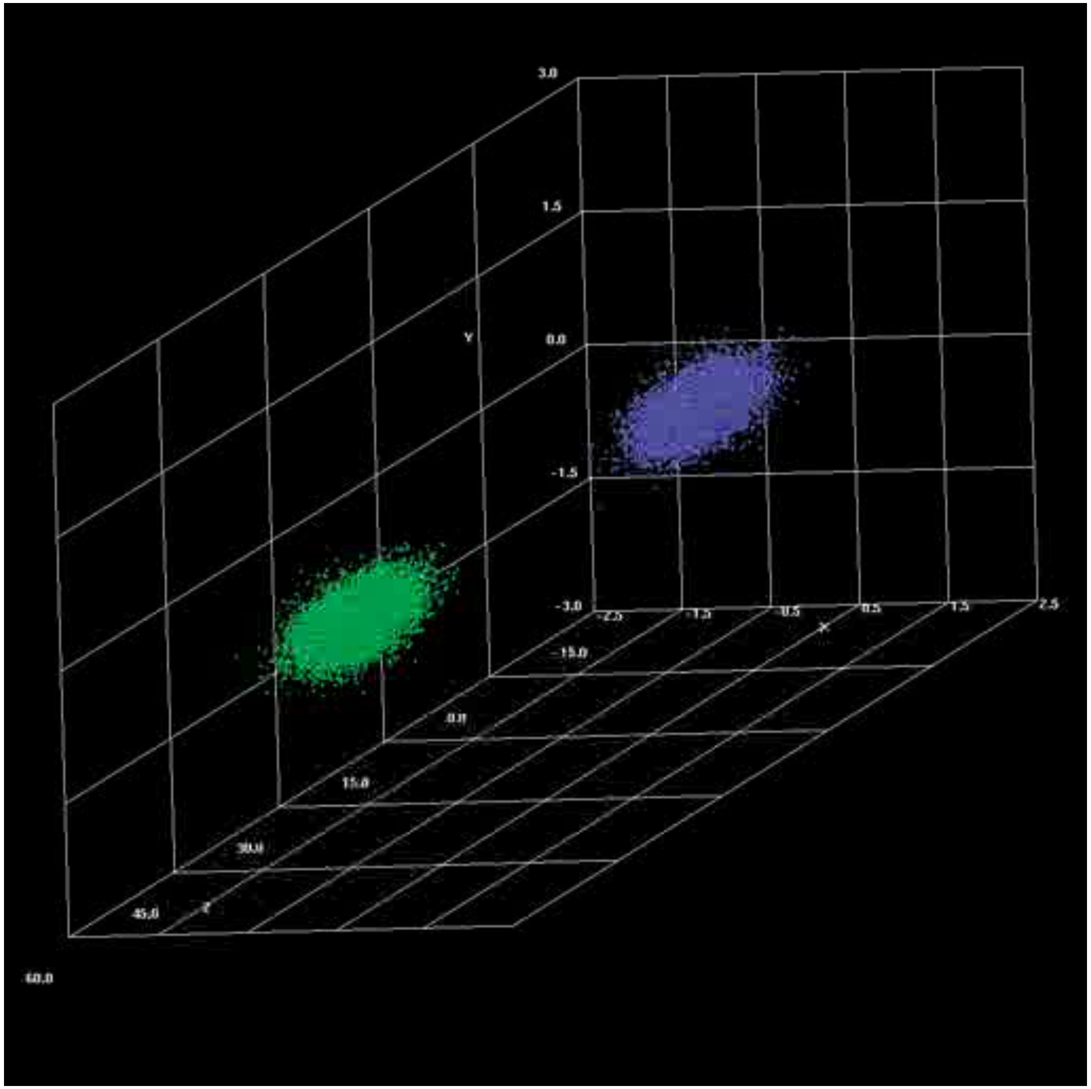
- Accelerator control does not often employ advanced controls techniques
  - Accelerators are build by physicists and control application by developers
  - Control theory the domain of research engineers
    - Accelerators do not fit into the standard "plant" paradigm of controls theorists

- Experimental machines
  - In past, machines could be operated open loop by experience
  - New machine w/ requirements too stringent for manual operation
    - Spallation Neutron Source (SNS)
    - Rare Isotope Accelerator (RIA)
    - International Linear Collider (ILC)

- Production facilities – desire for automation
  - Medical treatment facilities
  - Industrial accelerators

4.1 Electron-Positron Beam Collision
(Does Not Include Secondary Particle Creation)

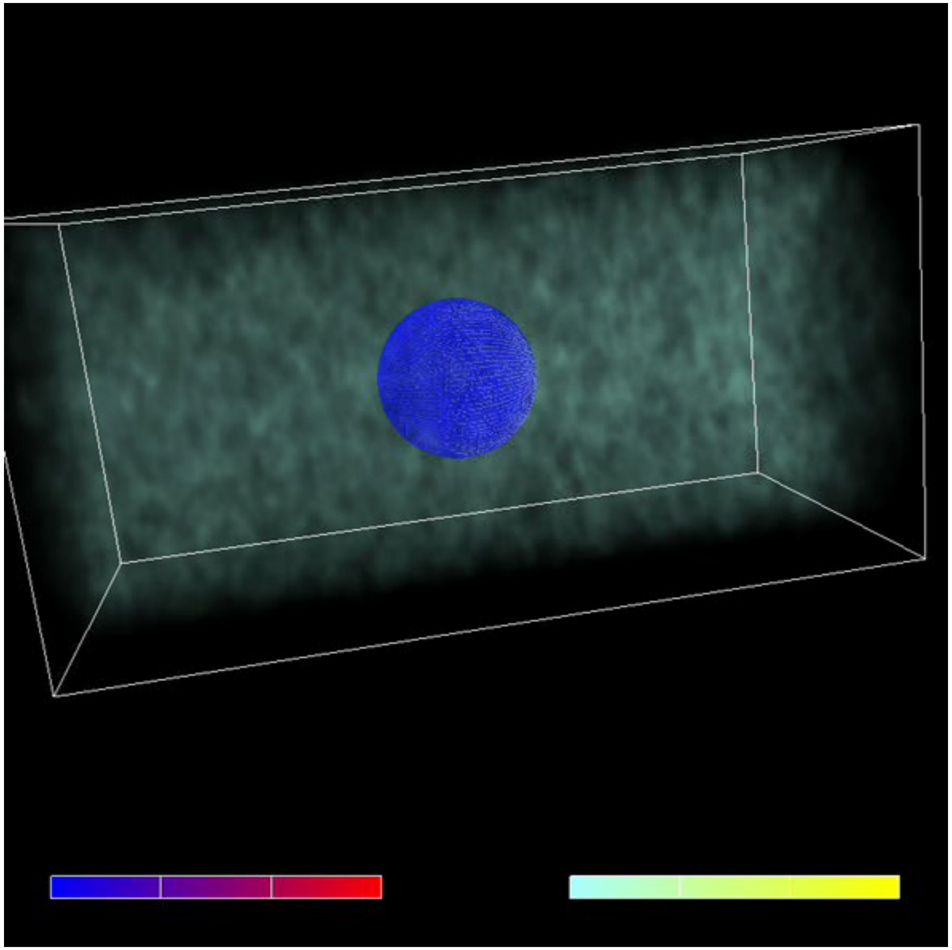
e^-/e^+ beam collision simulation, R.Ryne, J. Qiang, Lawrence Berkeley laboratory



4.1 Two Stream Instability

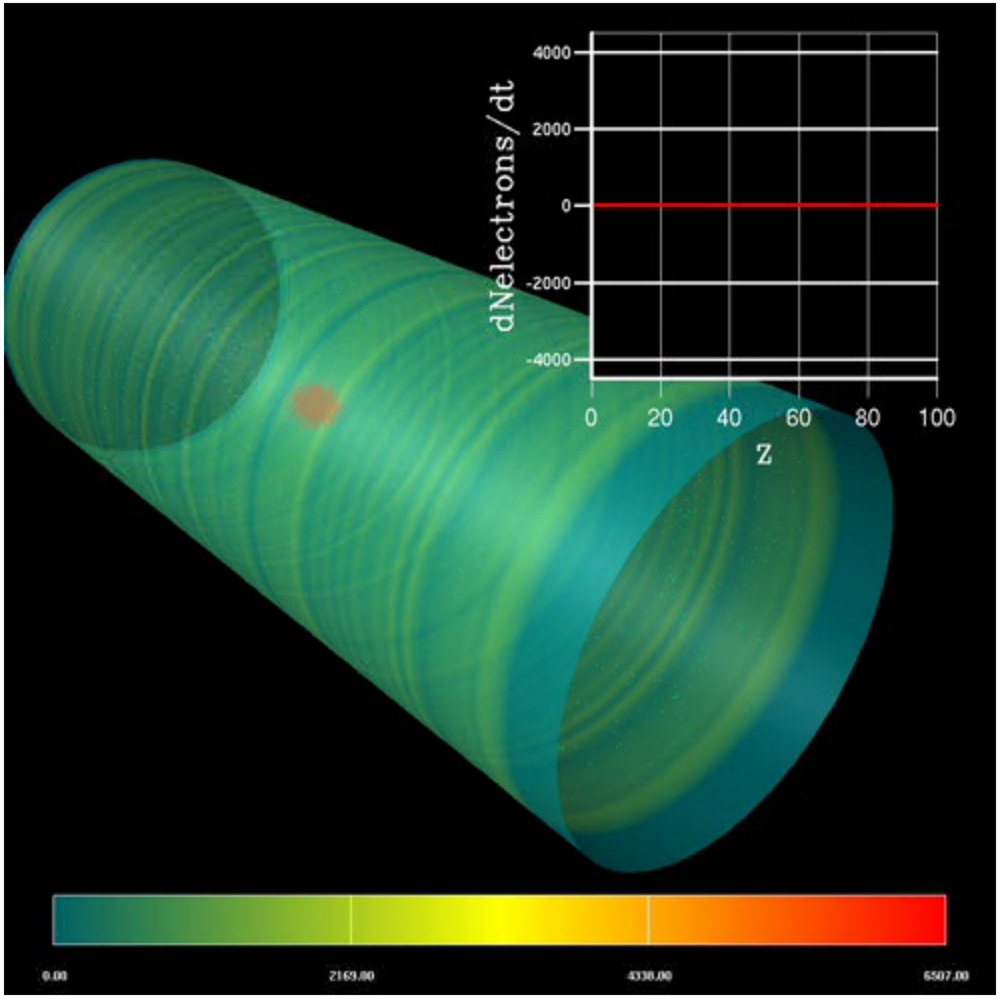
Background Electron Cloud and Proton Beam

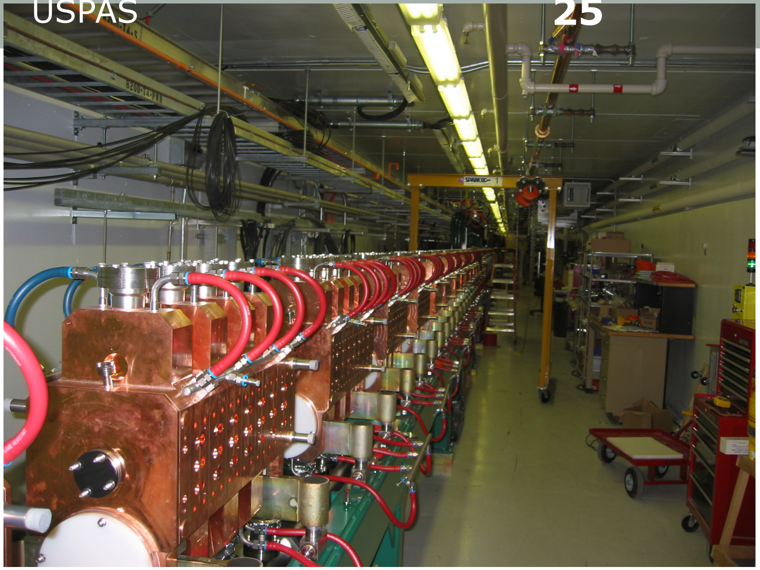
Simulation by Andreas Adelmann, Paul Scherr Institute, Villigen, Swizterland



4.3 Multiple Impacting (Multipacking)
Electron Oscillations in Beam Pipe - Degradation

Simulation by Andreas Adelmann, Paul Scherr Institute, Villigen, Swizterland





5. Conclusions

- Accelerators are Big Science
  - Big budgets
  - Long-term goals
  - Multi-disciplinary
- Control systems
  - We shall see that large and complicated control systems are necessary to operate these large machines.
  - Complex software systems comprise much of the accelerator control system.
- Control and automation
  - Most accelerator control system are based on Supervisory Control and Data Acquisition (SCADA)
  - Control theory is an open field in accelerator control.

Supplemental

- Control Problems

4. Control Theory and Accelerators

Example - Distributed Steering Algorithm

ISSUES

- We do not know state $\mathbf{z}(s) = (x, x', y, y', z, z')$
  - Have data only at BPM locations $\{s_0, s_1, s_2, \ldots\}$
  - BPMs provide only position coordinates (x,y,z)
  - Noise and misalignments
- Approach
  - State Estimator to reconstruct momentum coordinates
  - Multistage Network Model to approximate $\mathbf{z}(s)$
  - Optimal Control to minimize J

4. Control Theory and Accelerators

Example - Distributed Steering Algorithm

Basic Idea - rather than minimizing beam position errors at discrete BPM locations, we minimize a functional J of the beam state $\mathbf{z}(s)$ throughout the beamline

$$\mathbf{z} \equiv \begin{pmatrix} x & x' & y & y' & z & z' & 1 \end{pmatrix}^T$$

- The steering *objective* is thus defined by a functional J

- Functional J is decomposed into N terms J_n, one for each stage n
  - The sub-functional for each stage n is has the form

$$J_n(\mathbf{z}_n, \mathbf{u}_n) \equiv \frac{1}{2}\int_{s_n}^{s_{n+1}} \mathbf{z}(s)^T \, \mathbf{Q}_n \mathbf{z}(s) ds$$

where

$\mathbf{Q}_n$ – symmetric, positive semi-definite matrix

$\mathbf{z}(s) = \square_n(\mathbf{u}_n; s)\mathbf{z}_n$

3.2 Control Theory and Accelerators
Acceleration - Cavity Tuning/Klystron Phasing

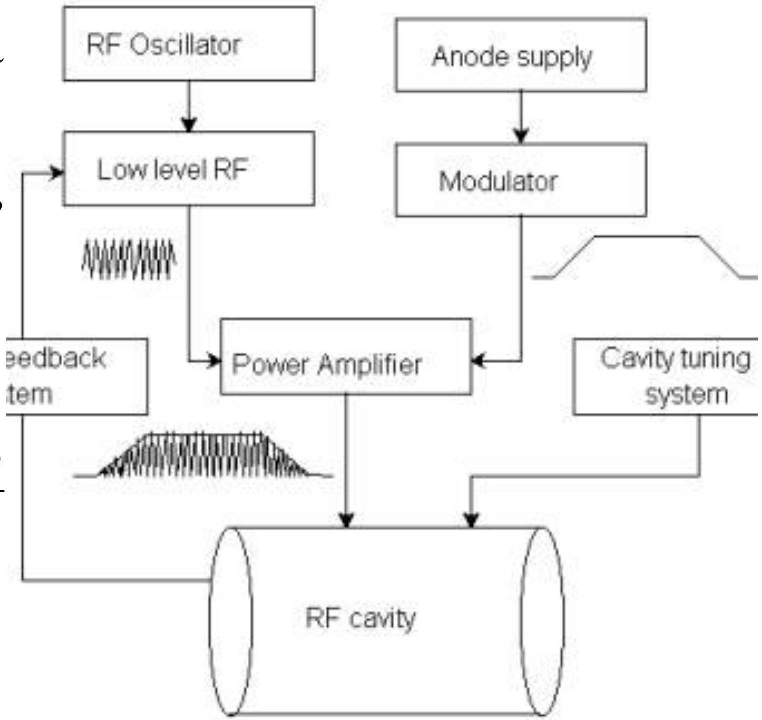
Consider an RF source of form $E_0\cos(\omega t+\phi_0)$, $\omega = 2\pi f$

- The phase $\phi(s)$ and energy $W(s)$ of a

$$W(s) = W_0 + qZ\int_0^s E_z(\sigma)\cos(\phi(\sigma))d\sigma,$$

$$\phi(s) = \phi_0 + \int_0^s k(\sigma)\,d\sigma,$$

where $\quad k(s) \equiv \dfrac{2\pi}{\beta(s)\lambda}, \qquad \beta \equiv \dfrac{v(s)}{c}$

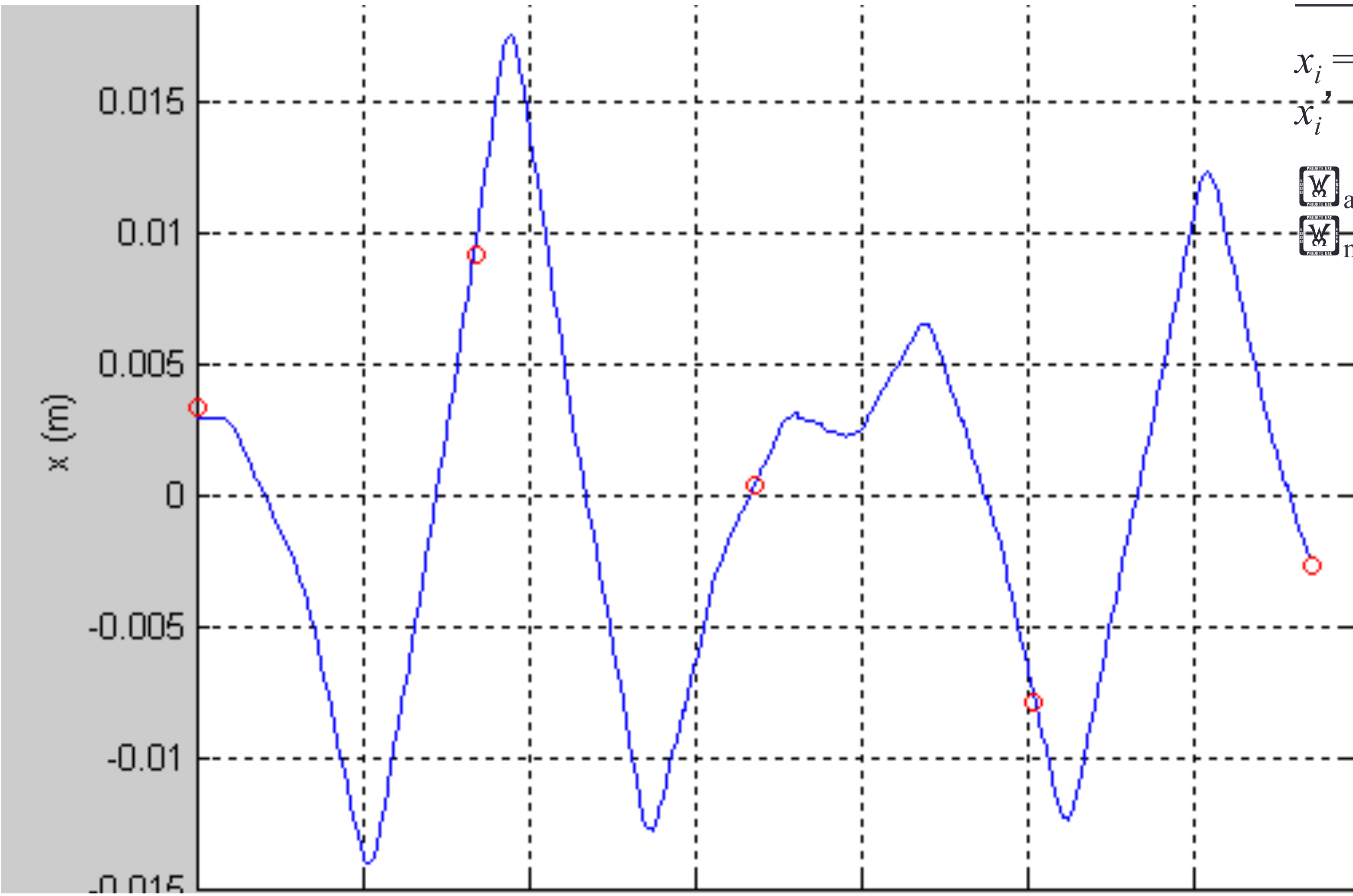


- Must tune the cavity to properly shape the fields $E_z(s)$
- Must phase the klystrons to that of the particle $\phi(s)$

4. Control Theory and Accelerators

Example - Distributed Steering Algorithm

Simulation Results – Estimating state vector $\mathbf{z}_n$ at each stage



Parameters

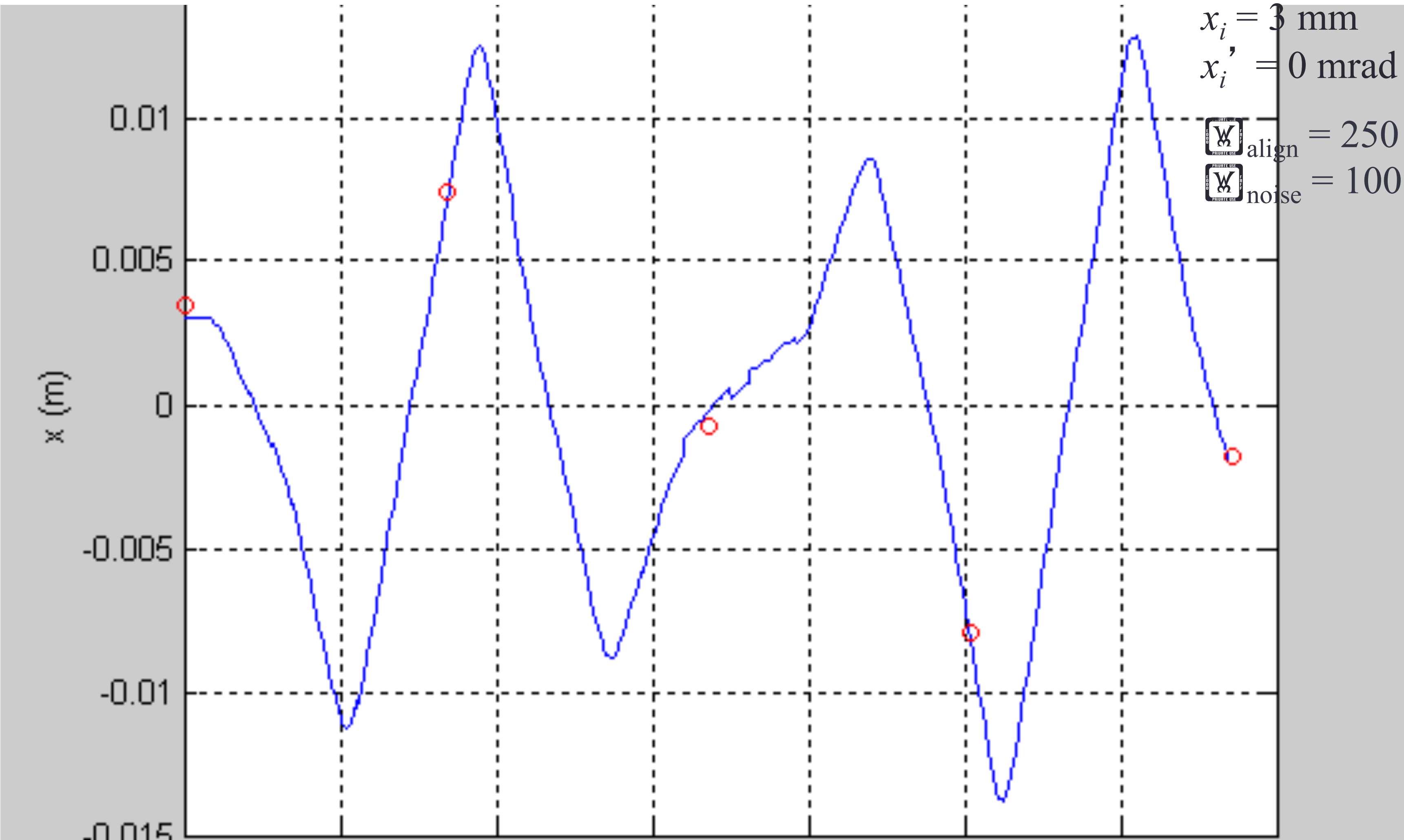
$x_i = 3$ mm
$x_i' = 0$ mrad

$\sigma_{align} = 100\ \mu m$
$\sigma_{noise} = 100\ \mu m$

4. Control Theory and Accelerators

Example - Distributed Steering Algorithm

Simulation Results – Estimating state vector $\mathbf{z}_n$ at each stage



Parameters

$x_i = 3$ mm

$x_i' = 0$ mrad

$\sigma_{align} = 250\ \mu$m

$\sigma_{noise} = 100\ \mu$m

4. Control Theory and Accelerators

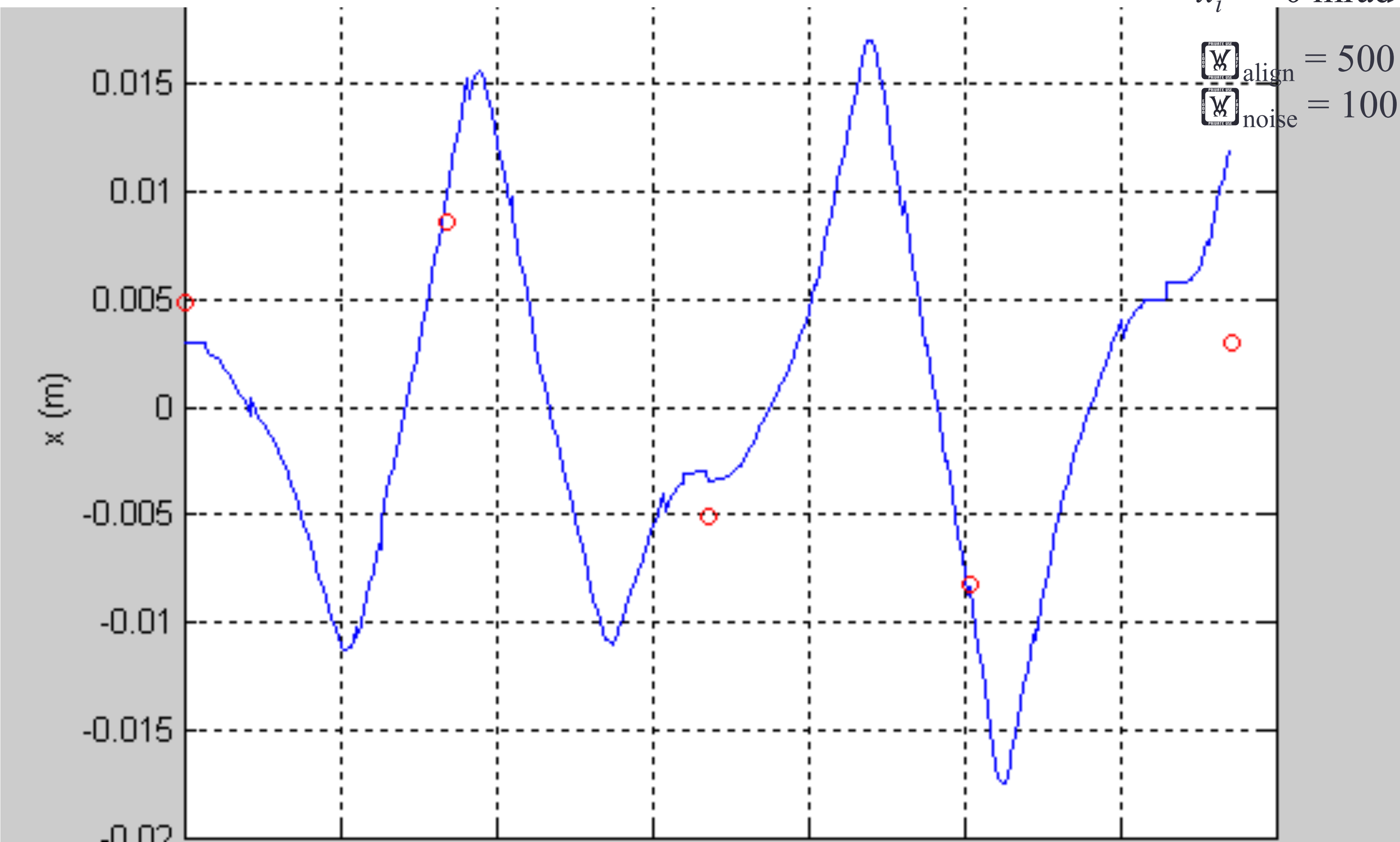
Example - Distributed Steering Algorithm

Simulation Results – Estimating state vector $\mathbf{z}_n$ at each stage

<u>Parameters</u>

x_i = 3 mm
x_i' = 0 mrad

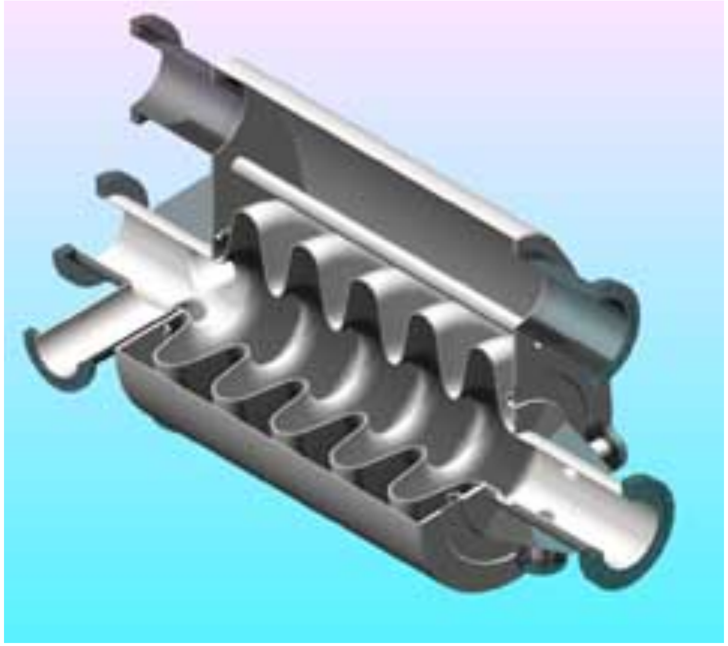
σ_{align} = 500 μm
σ_{noise} = 100 μm



2.2 Accelerating Structures

Super-Conducting Elliptical Cavity

- Design for very high energy > 500 MeV
- Very high peak electric fields ~100 MV/m
- One design can accommodate a range of energy values
- Less RF power but requires cryostats



CAD drawing of a super-conducting cavity elliptic cavity with 5 “gaps”