USPAS Summer 2008:

Beam Dynamics Experiments on the University of Maryland Electron Ring (UMER)

Instructors:

Rami A. Kishek
Santiago Bernal
Ralph Fiorito
Patrick G. O'Shea

My contact info:
ramiak@umd.edu
301-405-5012

Staff:

Brian Beaudoin
Max Cornacchia
Don Feldman
Irving Haber
Diktys Stratakis
David Sutter
J. Charles T. Thangaraj
Chao Wu

Outline

1. People Introductions

2. Course Outline

3. Administrative Issues

4. Review of Accelerator Physics / Introduction to Space Charge

5. Overview of UMER

Your backgrounds

- What accelerator courses have you taken?
- Any experimental experience?
- MATLAB?

Course Outline

		9:30 AM - 10:40 AM **Lecture 1**		10:50 AM - NOON **Lecture 2**		1 PM - 4 PM **Station 1** *UMER*	**Station 2** *LSE*	**Station 3** *Hughes*	**Offline**
Week 1									
Mon	**16**	Course Organization + Intro to UMER Beam Dynamics	Kishek	Diagnostics + Source Physics	Bernal, Haber	Safety; Diagnostcs; Sources			*Alternate: Breadboard*
Tue	**17**	Non-intercepting diagnostics	Sutter	Imaging and Image Processing	Kishek	Imaging; Tomography	Imaging; Imaging		Rotating Coil; Rotating Coil
Wed	**18**	Phase-Space Mapping / Tomography	Stratakis	*Tomography Morning Lab / on UMER*		Longitudinal (IM / Laser)	Monitors		Solenoid
Thu	**19**	Magnets and measurements	Bernal	*Tomography Morning Lab / on UMER*		Longitudinal (IM / Laser)	Monitors		Solenoid
Fri	**20**	Optical Transition Radiation	Fiorito	OTR demo (RC1)		Quad-scan (IC2)	*End early, by 2 PM*		Analysis/Writing
Week 2									
Mon	**23**	Longitudinal 1: Perturbation generation and Waves	O'Shea	Longitudinal 2: Beam End Erosion and Induction Cell	Beaudoin	Longitudinal (IM / Laser)	Monitors		Solenoid
Tue	**24**	Tune Measurement	Sutter	*Morning Lab*		Ring Dynamics	Energy Analyzer	Sources	BPM Calibration / Report Writing
Wed	**25**	Energy Analyzer Measurements	Kishek	*Morning Lab*		Ring Dynamics	Energy Analyzer		BPM Calibration / Report Writing
Thu	**26**	Emittance Measurement (Quad-scan/Pepper-pot/Slit)	Bernal	*Morning Lab*		Ring Dynamics	Energy Analyzer		BPM Calibration / Report Writing
Fri	**27**	*Annapolis: Student Presentations*							

Experiments

	Time / Group	10:30-11	11-11:30	11:30-N	N-12:30	12:30-1	1-1:30	1:30-2	2-2:30	2:30-3	3-3:30	3:30-4
WEEK 1												
Mon 16	**1**						**Safety Training**		S1, Sources/UMER, Santiago/Dave			
	2				**Lunch**				S2, Sources/LSE, Brian/Eric			
	3											
Tue 17	**1**						D2 Imaging/UMER Rami/Diktys			D3 Tomography/UMER Diktys/Rami		
	2				**Lunch**		D7 Imaging/LSE, Ralph/Brian			M2, Rotating Coil, Santiago/Jonny		
	3						**Safety Training**			D7 Imaging/LSE, Ralph/Brian		
Wed 18	**1**	*Free*					M1, Solenoid Profile, Santiago/Jonny					
	2	D3 Tomography/UMER Diktys/Rami			**Lunch**		D6, Monitors/LSE, Dave		*Free*			
	3	M2, Rotating Coil, Santiago/Jonny					L1, Logitudinal Dynamics/UMER, Charles/Brian					
Thu 19	**1**	M2, Rotating Coil, Santiago/Jonny					L1, Logitudinal Dynamics/UMER, Charles/Brian					
	2	*Free*			**Lunch**		M1, Solenoid Profile, Santiago/Jonny					
	3	D3 Tomography/UMER Diktys/Rami					D6, Monitors/LSE, Dave		*Free*			
Fri 20	**ALL**	D5 OTR/UMER, Ralph/Don			**Pizza**	D4, Quad-Scan/UMER Bernal						
WEEK 2												
Mon 23	**1**						D6, Monitors/LSE, Dave		*Free*			
	2				**Lunch**		L1, Logitudinal Dynamics/UMER, Charles/Brian					
	3						M1, Solenoid Profile, Santiago/Jonny					
Tue 24	**1**	R1 Resonances/UMER, Santiago/Dave/Chao						R2, Tune Measurement/UMER, Dave/Santiago/Chao				
	2	L2 Energy Analyzer/LSE, Brian/Rami/Charles				**Lunch**		*Free*				
	3	S3 Sources/HUGHES, Peter/Don						*Free*				
Wed 25	**1**	*Free*						*Free*				
	2	R1 Resonances/UMER, Santiago/Dave/Chao				**Lunch**		R2, Tune Measurement/UMER, Dave/Santiago/Chao				
	3	L2 Energy Analyzer/LSE, Brian/Rami/Charles						*Free*				
Thu 26	**1**	L2 Energy Analyzer/LSE, Brian/Rami/Charles						*Free*				
	2	*Free*				**Lunch**		*Free*				
	3	R1 Resonances/UMER, Santiago/Dave/Chao						R2, Tune Measurement/UMER, Dave/Santiago/Chao				
Fri 27	**ALL**	*Presentations*										

Annapolis – Instructor on duty 7 PM - midnight

Mon 5/16 Santiago

Tue 5/17 Rami

Wed 5/18 Diktys

Thu 5/19 Brian and/or Charles

Mon 5/23 Santiago

Tue 5/24 Chao

Wed 5/25 Brian

Thu 5/26 Rami

Assignments and Grading

20%	Participation (assessment of all instructors)
30%	2 Lab reports wk 1 (both due 9:30 AM Fri. 6/20)
30%	2 Lab reports wk 2 (both due 9:30 AM Fri. 6/27)
20%	10 min. Presentation (Fri. 6/27): 1 exp. per student

Lab Report Content

- Background: describe experiment and explain objectives
- Data: summarize results
- Analysis of data and discussion
- Conclusions – what have you learned?

Presentation covers 1 experiment different from any in reports

Lab Report Topics

Choose 1 from each category (15% of grade each)

Sources and Diagnostics:

- Sources + Beam Monitors
- Imaging + Tomography

Magnets:

- Solenoid
- Rotating Coil

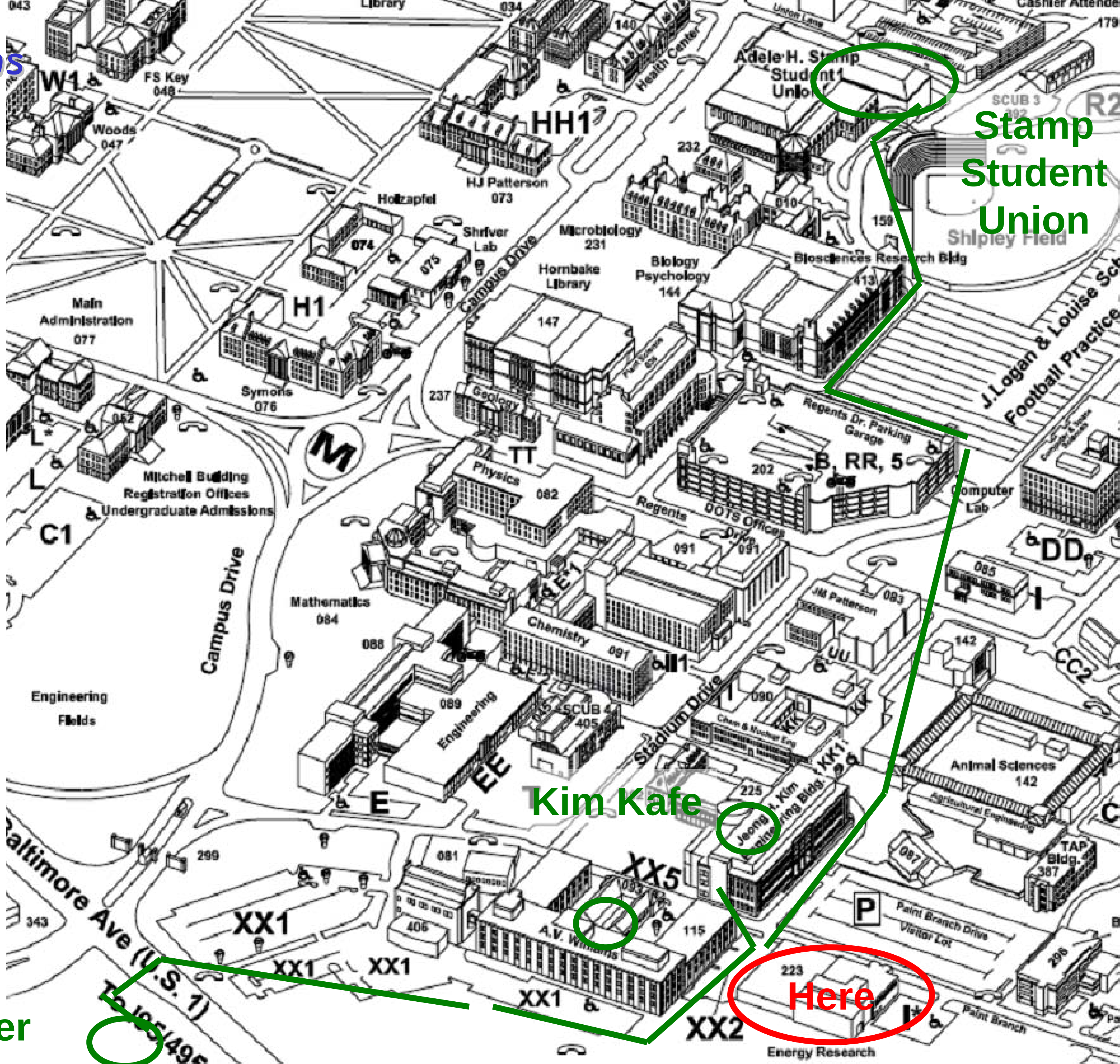
Longitudinal

- Longitudinal Dynamics
- Energy Analyzer

Ring Dynamics

- Tune Measurements
- Resonances

Lunch Options



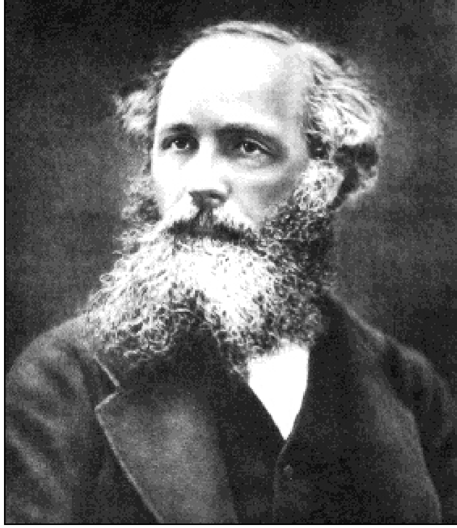
Shopping Center

Readings (Review)

- Space Charge:
  - Reiser, Sec. 4.2.1, 4.3.2
- Emittance and Phase Space
  - Reiser, Sec. 3.1, 3.2, Fig. 3.26
- Quadrupole and Solenoid Magnets
  - Reiser, Sec. 3.5, 3.4.4
- Child-Langmuir Law
  - Reiser, Sec. 2.5.1, 2.5.2

Quote of the Day ...

James Clerk Maxwell



Maxwell's Equations

Electromagnetic fields generated by charges and currents:

$$\nabla \bullet \mathbf{E} = \frac{\rho}{\varepsilon_o} \qquad \nabla \bullet \mathbf{B} = 0$$

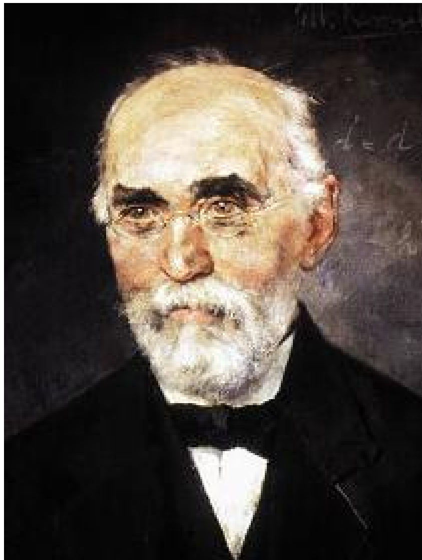
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \times \mathbf{B} = \mu_o \mathbf{J} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

Lorentz-Newton Force Law

Motion of charged particles due to electromagnetic forces:

$$\mathbf{F} = \mathrm{q}(\mathbf{E} + \mathrm{v} \times \mathbf{B}) = \frac{\mathrm{d}\mathbf{P}}{\mathrm{dt}}$$

Hendrik Lorentz
(1853-1928)



Notation, as in Reiser

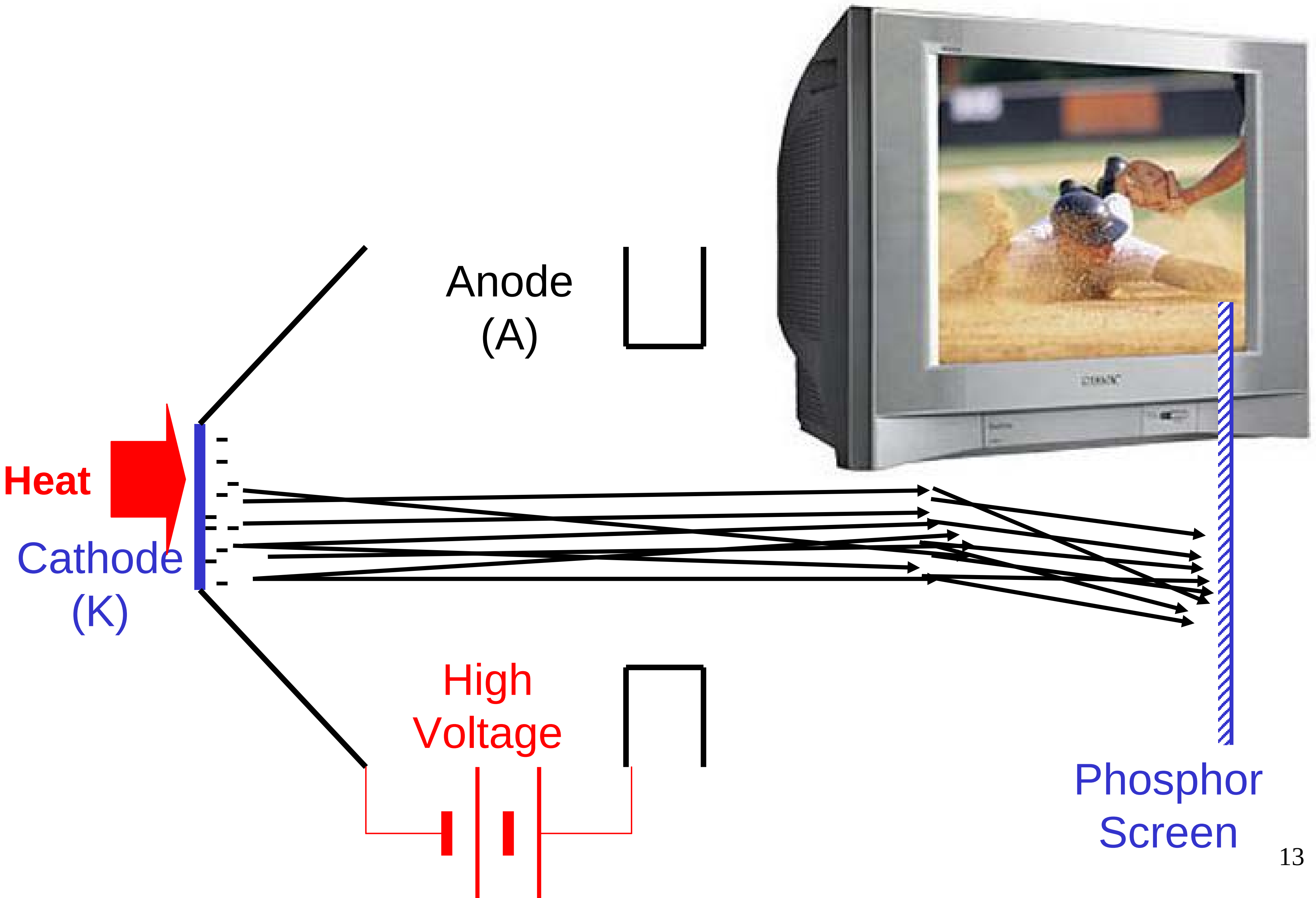
- q – Electric Charge
- **v** – Particle Velocity
- I – Beam Current
- **E** – Electric Field
- **B** – Magnetic Field
- m – Particle Mass
- ε_o – Permittivity of Free Space
- μ_o – Permeability of Free Space

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}}$$

$$\beta = \frac{v}{c}$$

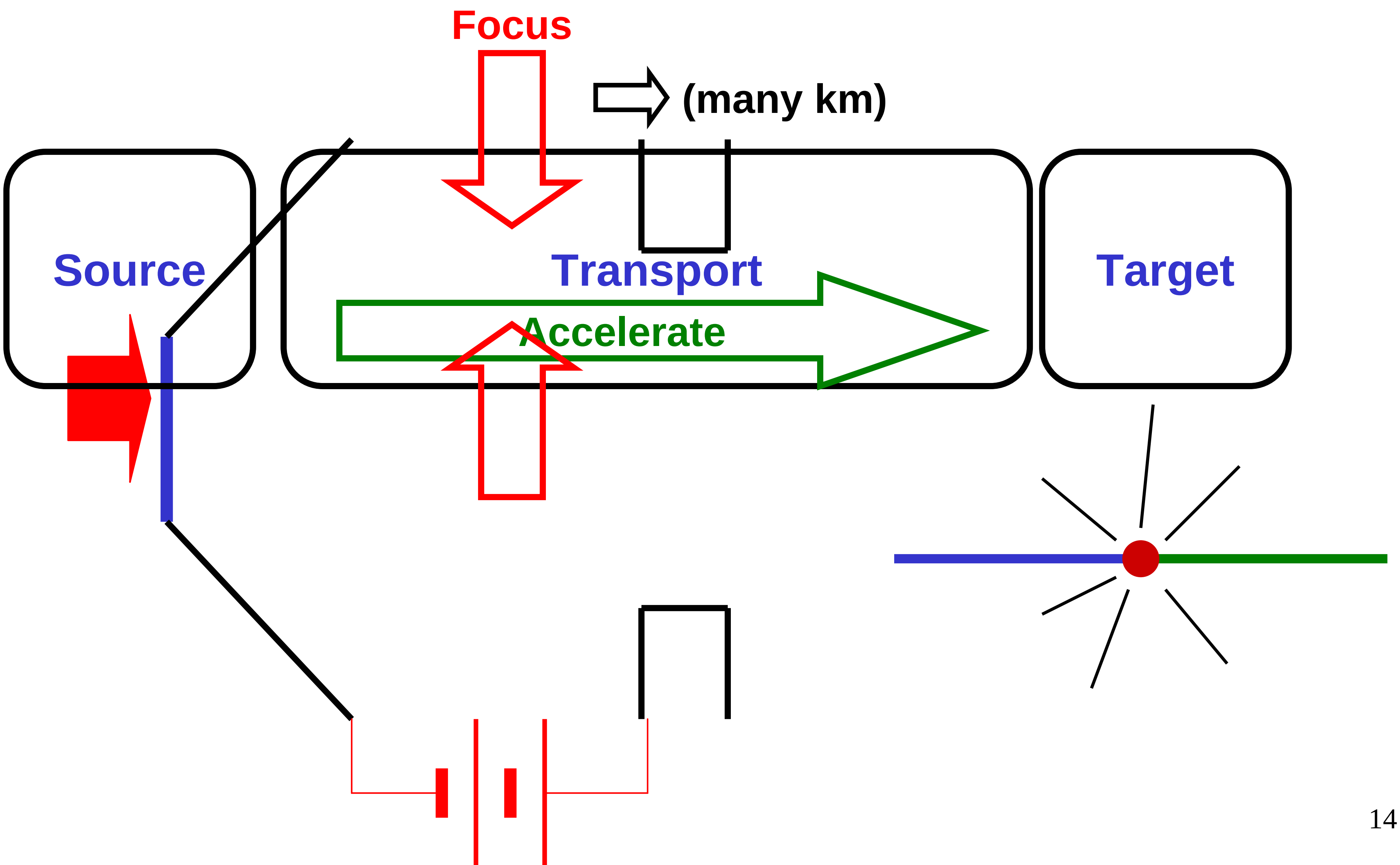
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Everyone has an accelerator at home

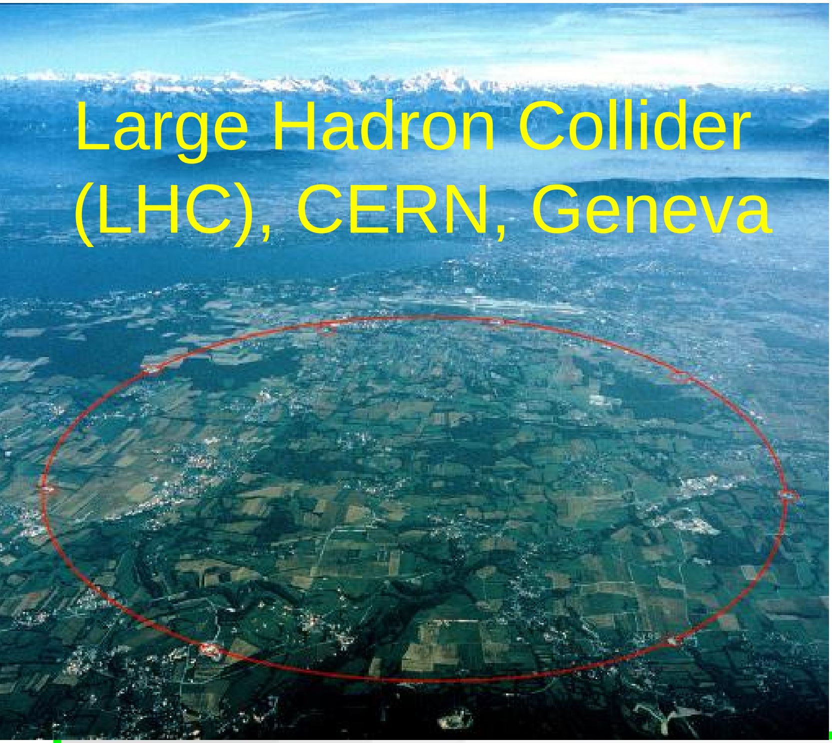


Accelerator Schematic

For this course, we are interested in beam itself, as a state of matter

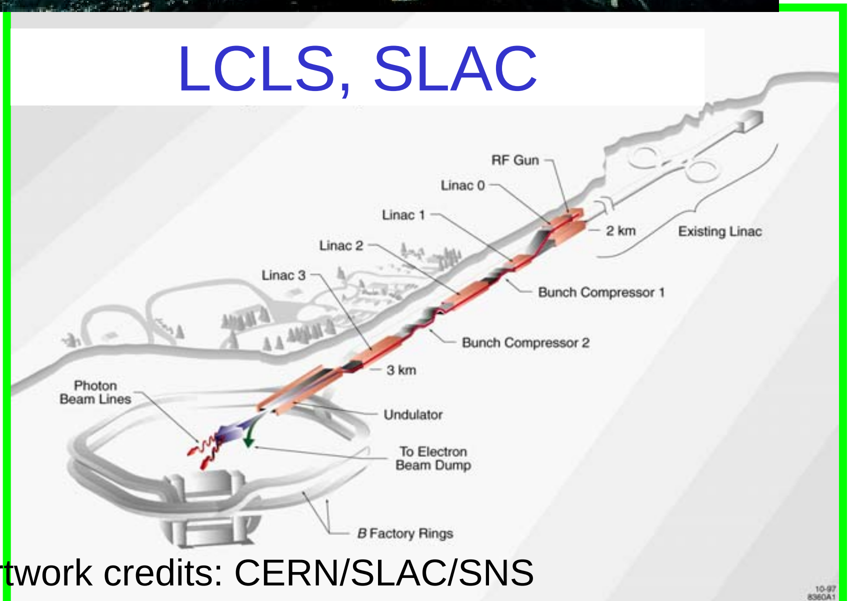


Growth of Accelerator Science



Modern Growth Areas:

- FEL + ERL Light Sources
- Pulsed Neutron Sources
- Medical Imaging and Therapy
- Muon / Neutrino Beams
- Rare Isotope Beams



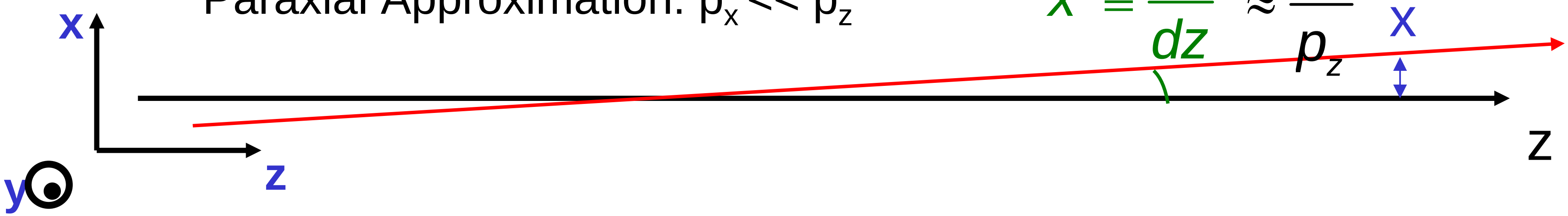
Artwork credits: CERN/SLAC/SNS

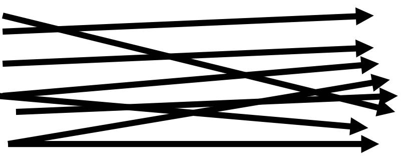
Goal: Generation and Preservation of High-Quality Beams

A beam is a collection of charged particles with a dominant velocity component

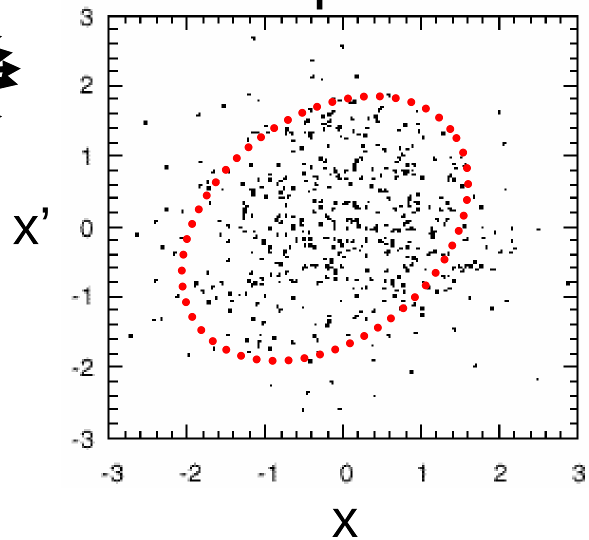
Paraxial Approximation: $p_x << p_z$

$$x' \equiv \frac{dx}{dz} \approx \frac{p_x}{p_z}$$





Phase Space



Quality Measures:

Emittance, ε:
Volume of phase space

Brightness, B:
Density of phase space

Intensity, χ:
Relative strength of forces

Beam Quality Measures - Definitions

rms Emittance	$\tilde{\varepsilon}_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$	
Normalized rms Emittance	$\tilde{\varepsilon}_{x,n} = \beta\gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$	Phase space volume - compactness
Normalized Ave Brightness	$\bar{B}_n = \frac{2I}{\pi^2 \varepsilon_{x,n} \varepsilon_{y,n}}$	Phase space density
Generalized Perveance	$K \equiv \frac{2I}{I_o (\beta\gamma)^3}$ $\quad I_o = \frac{4\pi\varepsilon_o mc^3}{q}$	Space charge energy / total kinetic energy
Intensity	$\chi \equiv \frac{K}{k_0^2 a^2}$	Dimensionless, transport dynamics

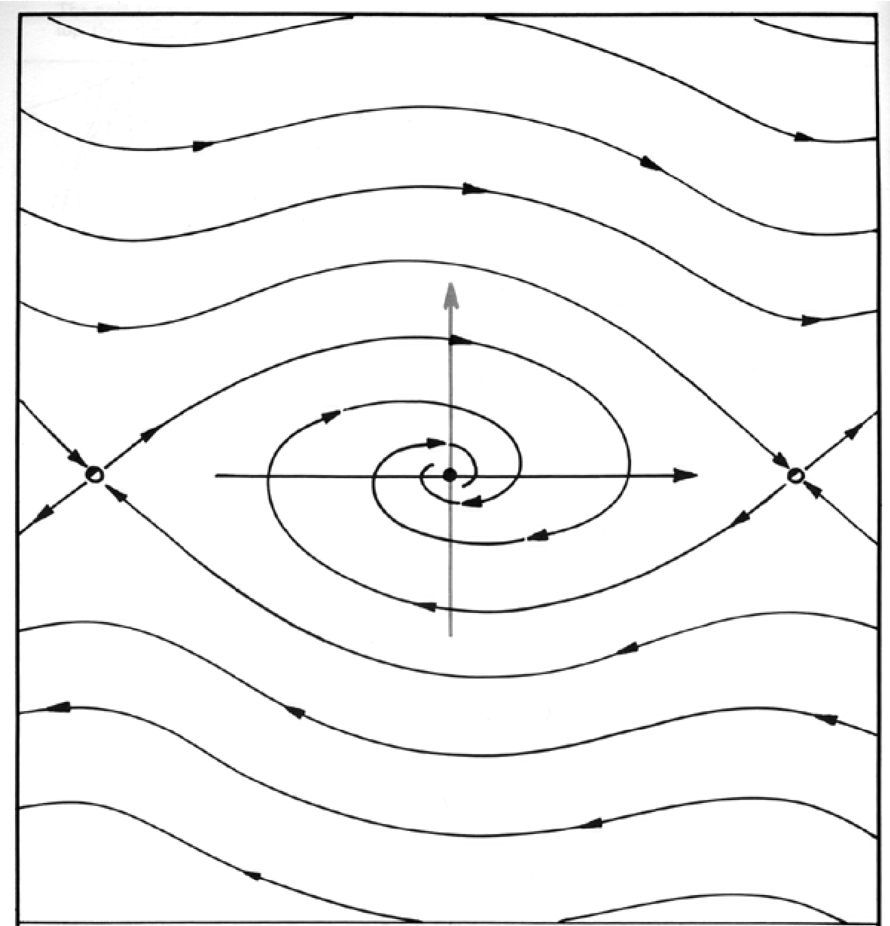
Can also show:

$$\chi = \frac{1}{1 + \frac{1}{K}\left(\frac{\varepsilon_n}{\beta\gamma a}\right)^2}$$

$$\bar{B}_n = \frac{I_o}{\pi} \frac{\beta\gamma}{\pi a^2} \left(\frac{\chi}{1-\chi}\right)$$

Phase Space

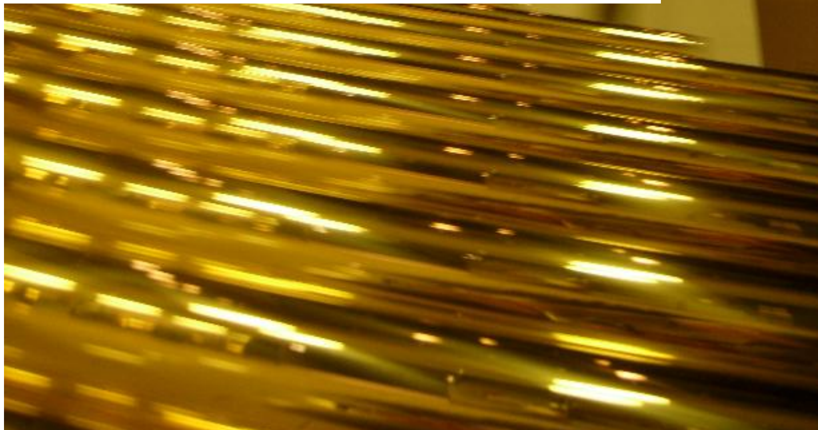
Wikipedia: *"In mathematics and physics, phase space is the space in which all possible states of a system are represented, with each possible state of the system corresponding to one unique point in the phase space."*



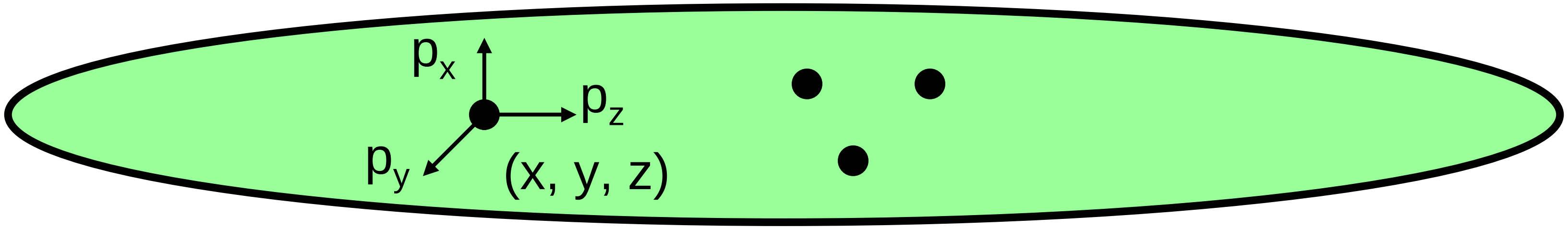
2.1.19. A more realistic example may be obtained by including the effects of friction in the hinge, and air resistance. Here is the phase portrait which results. Notice that it is very similar to the preceding portrait, but the equilibrium point at the origin is no longer a *center*. It has become an *attractor*. This is because any nearby trajectory, representing a

courtesy Abraham & Shaw

Dynamic phase portrait:
for any state, shows past history and future prediction



Phase Space for Beams



Each particle, need to specify 6 state variables (x, y, z, p_x, p_y, p_z)

N particles: State of entire system needs 6N variables to specify

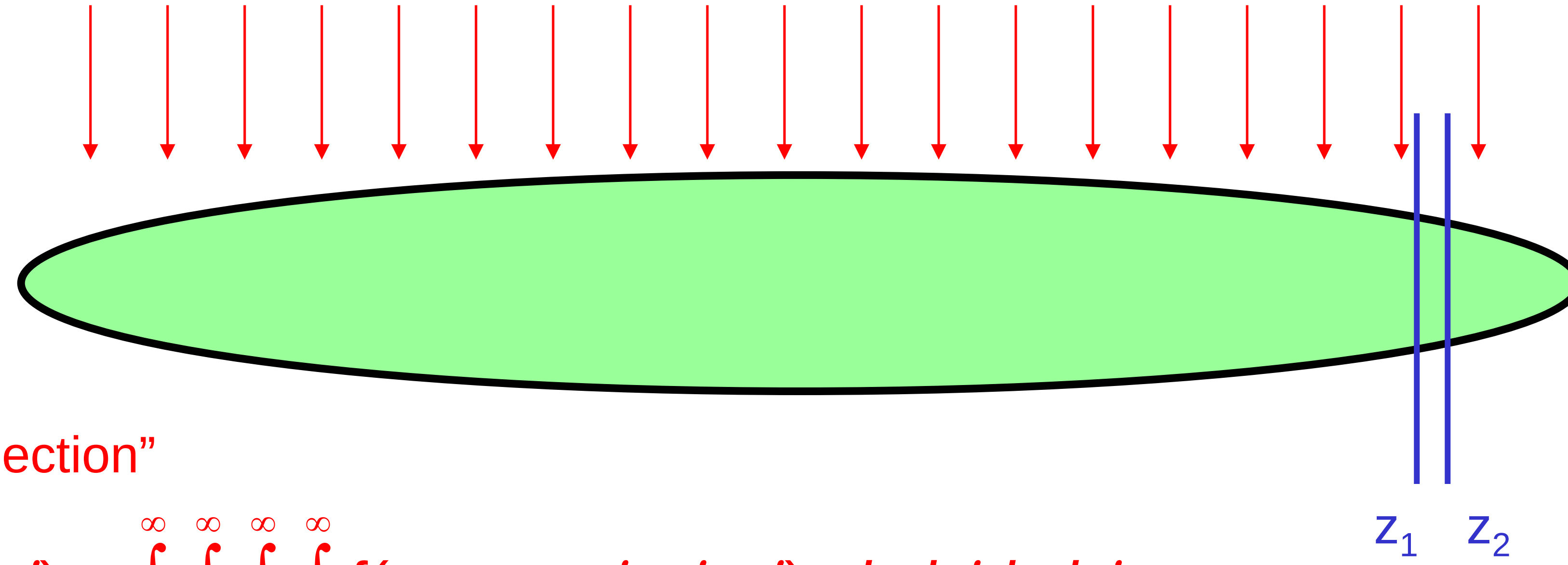
Beam "Distribution" representations:

- One point in 6N-dimensional phase space
- N points in 6-dimensional phase space
- Density of a "continuum" in 6-dimensional phase space (assumes an averaging process over specified "bins")
  $\Rightarrow$ $f(x, y, z, p_x, p_y, p_z)$ or $f(x, y, z, x', y', z')$

Beam distribution is a static phase portrait,
just a snapshot of one possible state of the system.

Phase Space Projections and Slices

6-D hard to visualize, so reduce dimensionality



"Projection"

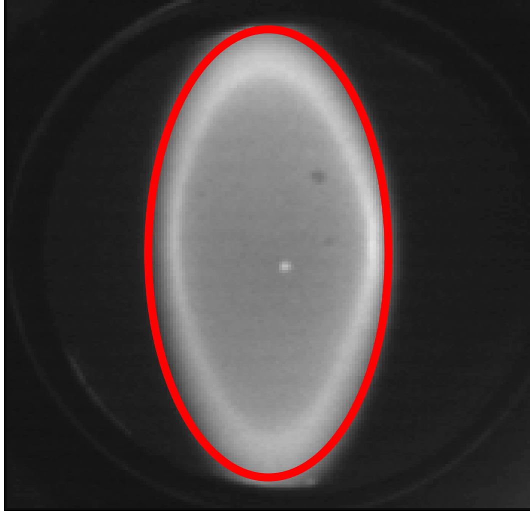
$$f(y,y') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x, y, z, x', y', z')\ dx\,dx'\,dz\,dz'$$

"Slice"

$$f(x,y,x',y') = \int_{-\infty}^{\infty}\int_{z_1}^{z_2} f(x, y, z, x', y', z')\ dz\,dz'$$

Beam density image is a projection onto 2-D

$$n(x,y) = \iint f(x,y,x',y')dx'dy'$$



Beam Ellipse

beam centroid

$$x_c = \langle x \rangle = \frac{\iint x n(x,y) dxdy}{\iint n(x,y) dxdy}$$

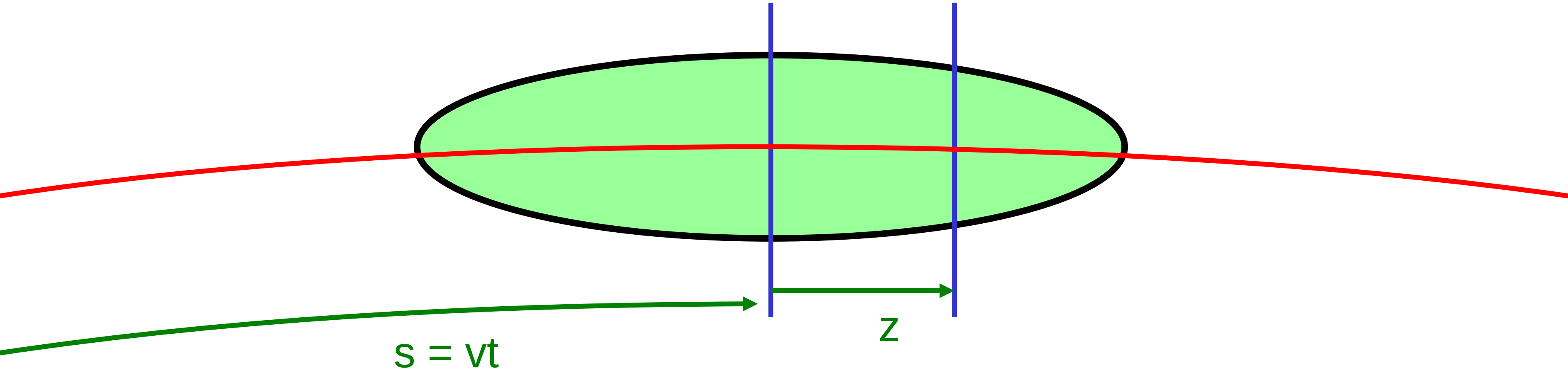
rms beam radius definition

$$x_{rms} = \tilde{x} = \sqrt{\langle x^2 \rangle} = \sqrt{\frac{\iint x^2 n(x,y) dxdy}{\iint n(x,y) dxdy}}$$

Similarly for y_c and y_{rms} …

For a uniform beam, a = 2 x_{rms} , b = 2 y_{rms}

Reference Trajectory and Coordinate System



s = distance along accelerator reference trajectory

z = distance in beam frame relative to midplane

Paraxial approximation: can change coordinates

$$t \rightarrow s = \beta c t$$

$$\frac{d}{dt} \rightarrow \beta c \frac{d}{ds}$$

Transverse particle motion under a linear external force

Assume a linear external force: $F_{ex} = -\gamma m\beta^2 c^2 \kappa_{xo}(s)x$

Assume no acceleration: $d\gamma/dt = 0$

$$\frac{dP_x}{dt} = \gamma m\ddot{x} = F_{ex}$$

Single-Particle Force Law

Change coordinates

$$\beta c\frac{dP_x}{ds} = \gamma m\beta^2 c^2 x'' = -\gamma m\beta^2 c^2 \kappa_{xo}(s)x$$

$$x'' = -\kappa_{xo}(s)x$$

Simplest type of focusing: Uniform Focusing

$\kappa_{xo}(s) = \kappa_{xo}$

$\kappa_{yo}(s) = \kappa_{yo}$

κ_{xo}, κ_{yo} are constants (independent of z)

units: κ_{xo}, κ_{yo} $[m^{-2}]$

$x'' = -\kappa_{xo}x$

$y'' = -\kappa_{yo}y$

Terminology: κ_{xo}, κ_{yo} = focusing strength

Solution? Harmonic Motion

$$x(s) = x_o \cos\left(\sqrt{\kappa_{xo}}\,s\right) + \frac{x_o'}{\sqrt{\kappa_{xo}}}\sin\left(\sqrt{\kappa_{xo}}\,s\right)$$

$$x'(s) = -x_o\sqrt{\kappa_{xo}}\sin\left(\sqrt{\kappa_{xo}}\,s\right) + x_o'\cos\left(\sqrt{\kappa_{xo}}\,s\right)$$

Initial conditions:

$x(0) = x_o$

$x'(0) = x_o'$

Betatron Oscillations, *will be periodic if $\kappa_o(s)$ is periodic*

$$k_{xo} \equiv \sqrt{\kappa_{xo}}$$

$$k_{yo} \equiv \sqrt{\kappa_{yo}}$$

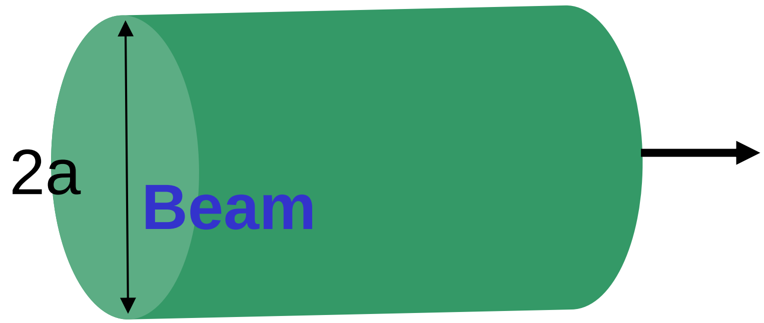
"Wavenumber"

Effect of Space Charge on Betatron Oscillations

$$x'' = -\kappa_{xo}(s)x + \frac{K}{a^2}x \equiv -\kappa_x(s)x$$

External force

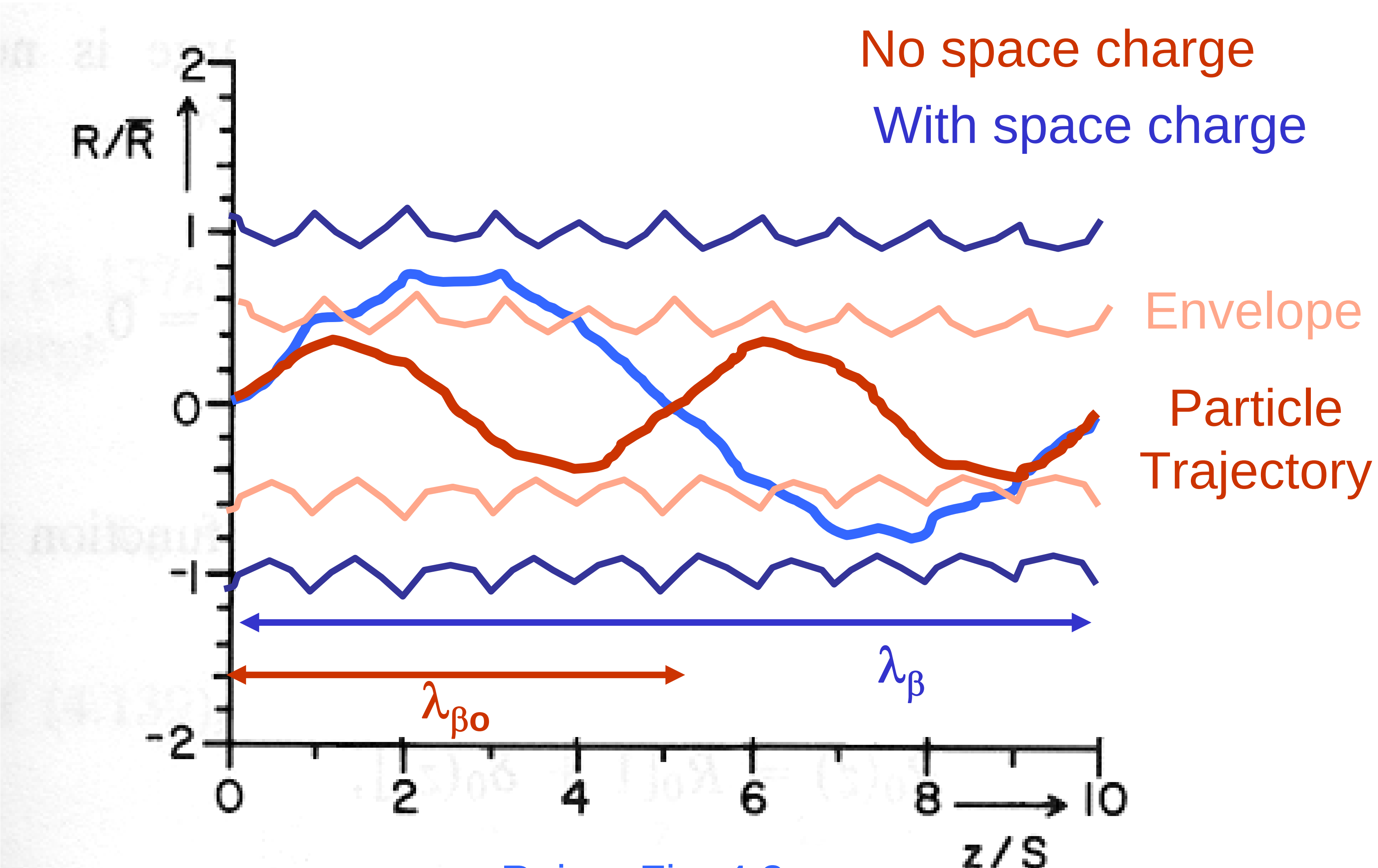
Space Charge Force
(from Gauss' Law)



$$\kappa_x(s) \equiv \kappa_{xo}(s) - \frac{K}{a(s)^2}$$

κ_x (with space charge) < κ_{xo} (without sc)

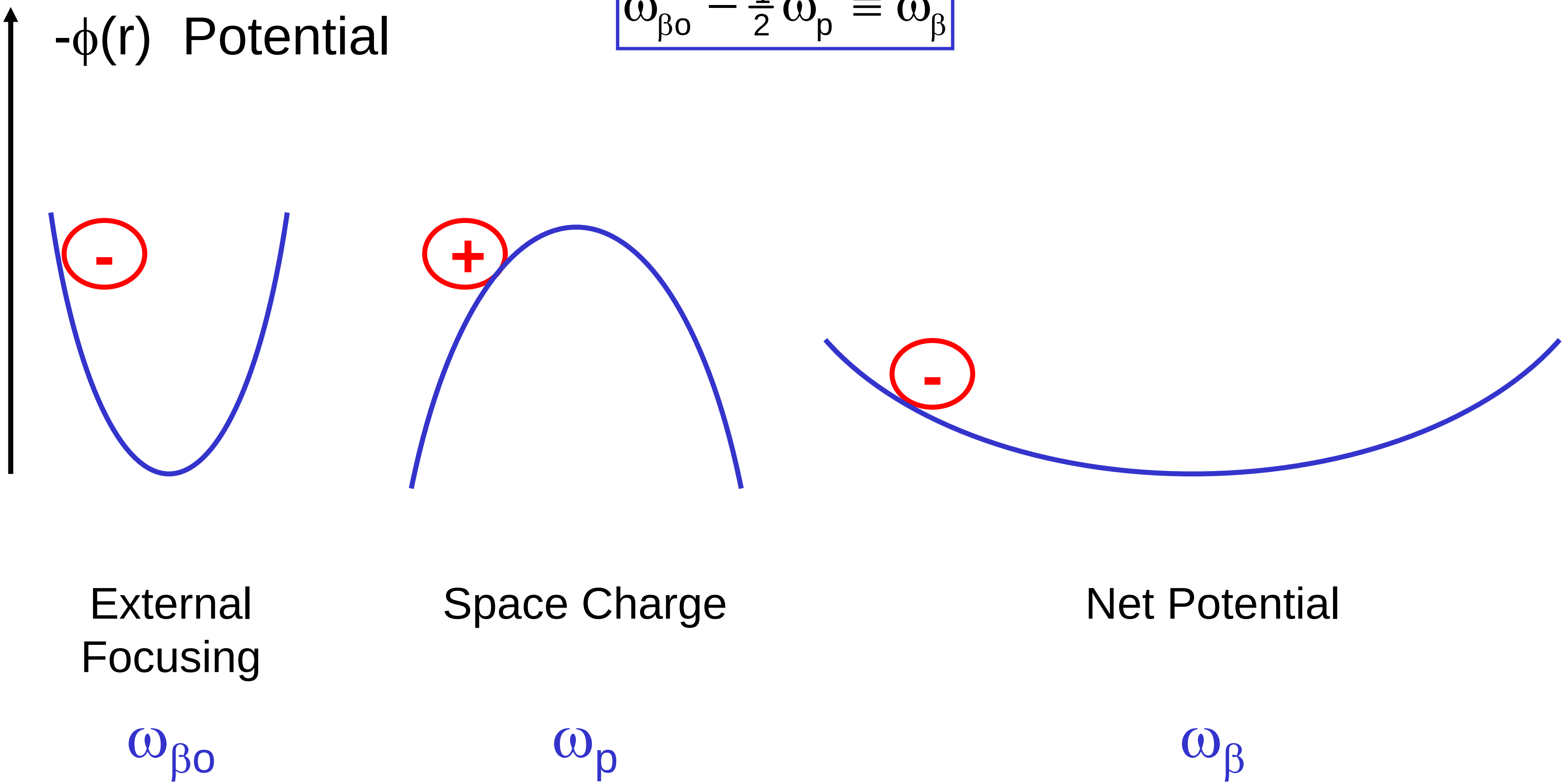
Effect of Space Charge on Betatron Motion in Periodic Lattice



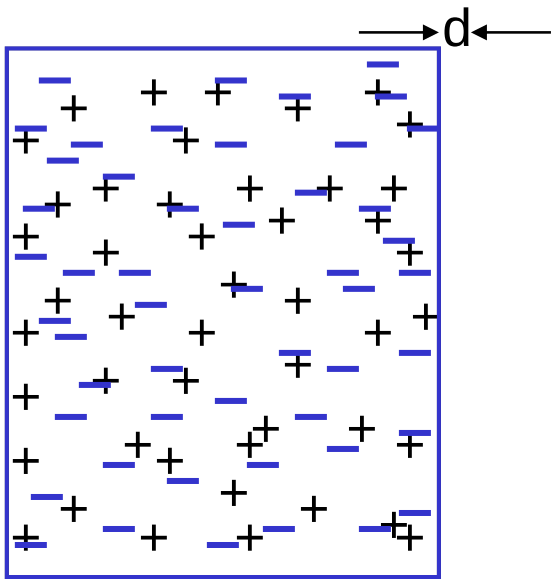
Reiser Fig. 4.3

Betatron and Plasma Frequencies

$$\omega_{\beta o}^2 - \tfrac{1}{2}\omega_p^2 \equiv \omega_\beta^2$$



A Beam with a Space Charge is a Plasma

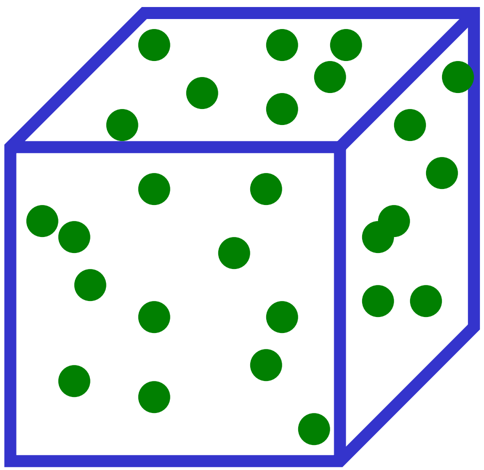


Plasma = Gas of charged particles

Plasma frequency – collective oscillation frequency

$$\omega_p \equiv \sqrt{\frac{e^2 n}{\gamma^3 m \varepsilon_o}} = \frac{\beta c\sqrt{2K}}{a}$$

Beam: External focusing force replace ion background



Debye length governs scale of density modulations

$$\lambda_D \equiv \left(\frac{\varepsilon_o k_B T}{e^2 n}\right)^{1/2} = \frac{\tilde{v}_x}{\omega_p} = \frac{\varepsilon}{2\sqrt{2K}}$$

Total number of particles with Debye Cube (or Sphere)

$$L \gg \lambda_D \gg n^{-1/3}$$

Summary of Key Frequencies and Wavelengths

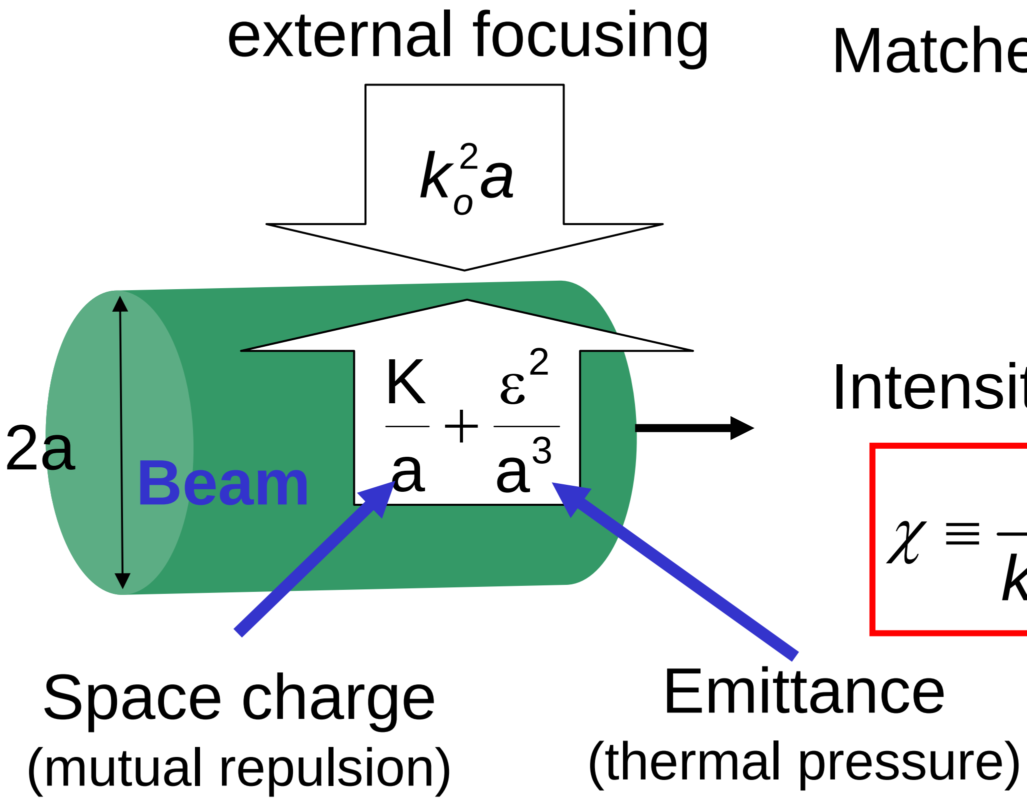
	Frequency	Wavenumber	Wavelength	Tune
Unit	rad/sec	m^{-1}	m	-
Definition	$\omega=2\pi f$	$k=\omega/v_o$	$\lambda=2\pi/k$	$\nu=C/\lambda$
Betatron (no space charge)	$\omega_{\beta o}$	$k_{\beta o}$ also k_{xo}, k_o	$\lambda_{\beta o}$	$\nu_{\beta o}$
Betatron (with space charge)	ω_{β}	k_{β}	λ_{β}	ν_{β}
Plasma	ω_p	k_p	λ_p	

Centroid behaves as single particle, oscillates at $\omega_{\beta o}$ (ignoring image forces)

Particles oscillate at the betatron frequency, ω_{β}

Collective structures (waves) oscillate at frequencies related to plasma freq.

Matched Beam: Force Balance for Stable Transport



Matched beam, Uniform focusing

$$k_o^2 a = \frac{K}{a} + \frac{\varepsilon^2}{a^3}$$

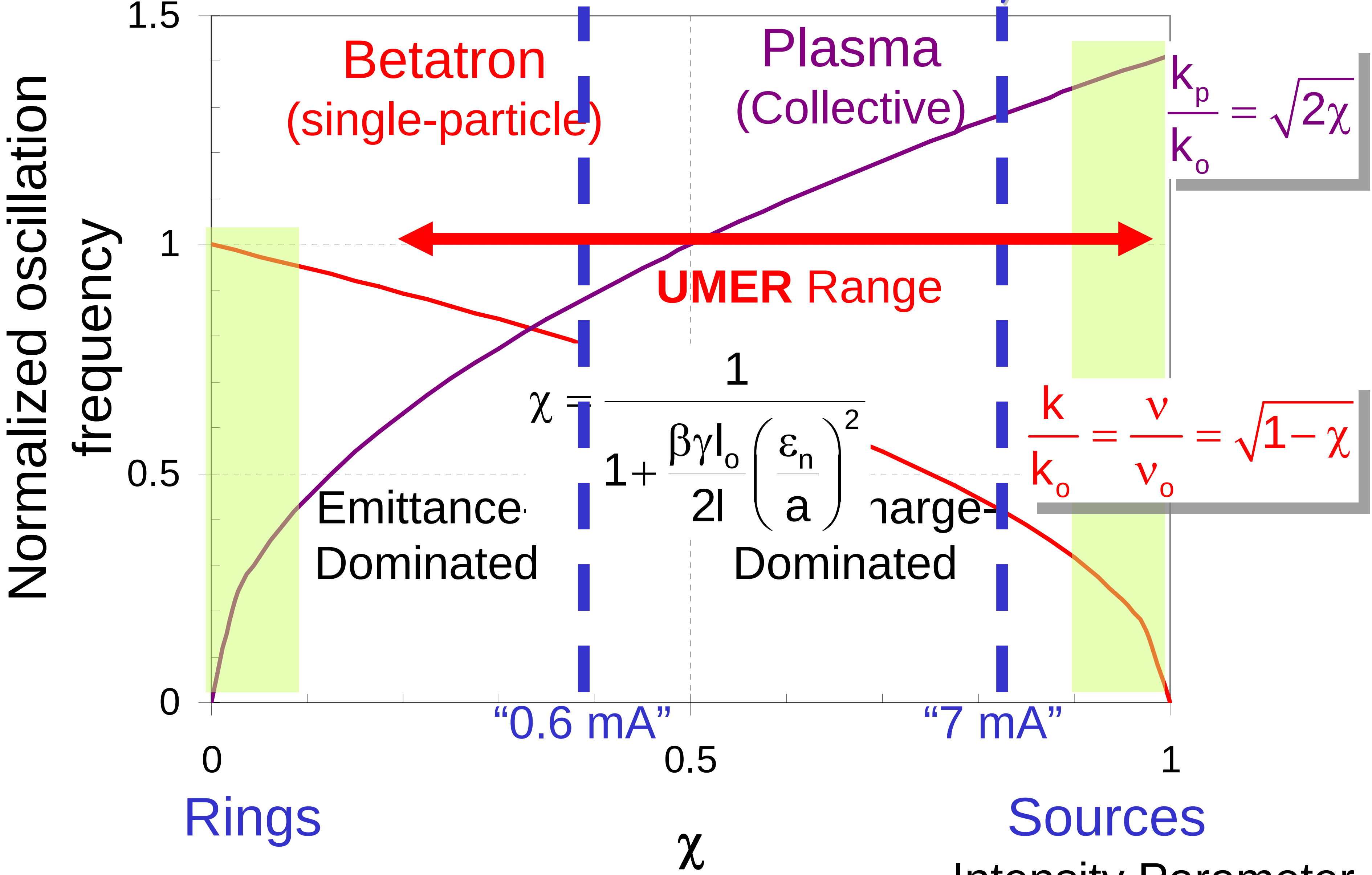
Intensity Parameter:

$$\chi \equiv \frac{K}{k_o^2 a^2} = \frac{\text{space charge force}}{\text{external focusing force}}$$

Emittance-Dominated	Space-Charge-Dominated
Space Charge as Perturbation to Single-particle orbits	Beam behaves as plasma Collective effects prevalent
Rings, Ultra-relativistic beams	Sources, Injectors

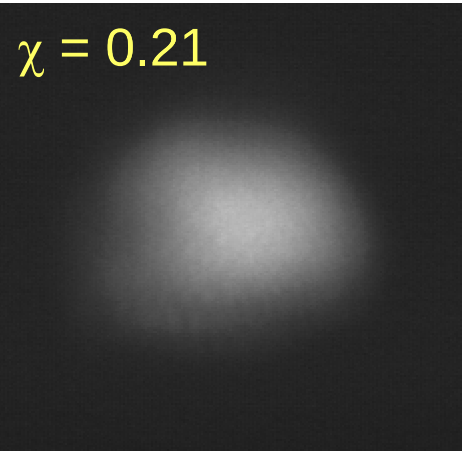
0 χ 1

Intense Beams Have Different Physics



M. Reiser, et al., PAC '99.

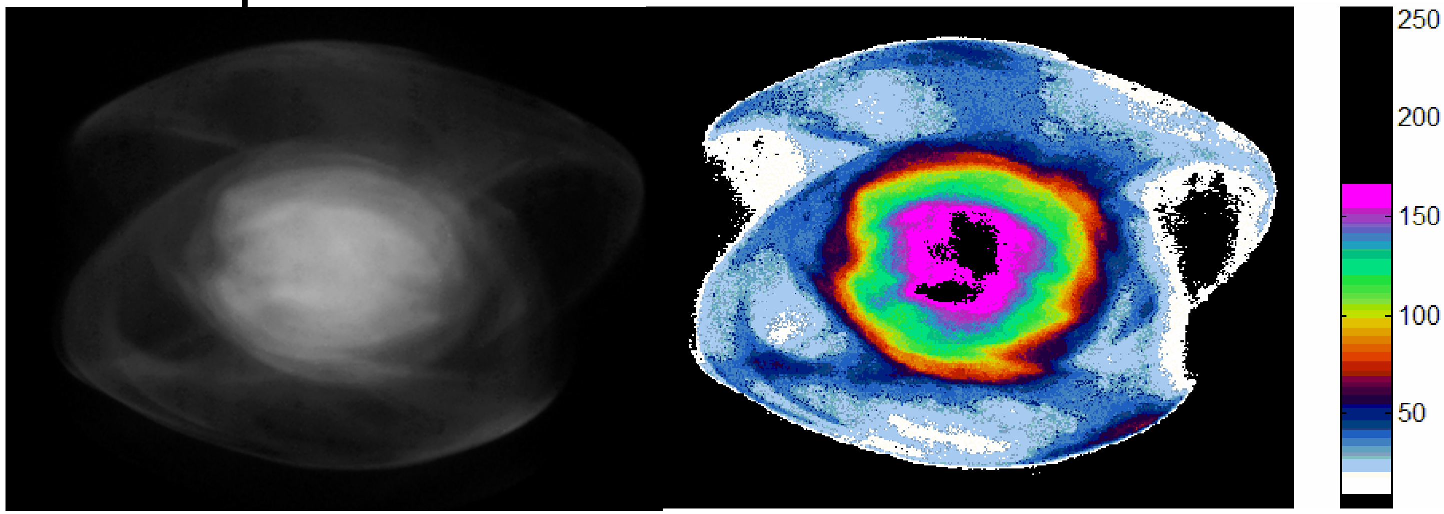
Examples of Beam Distributions



Emittance-Dominated

Beam Images from Phosphor screen

Color-coded to enhance halo



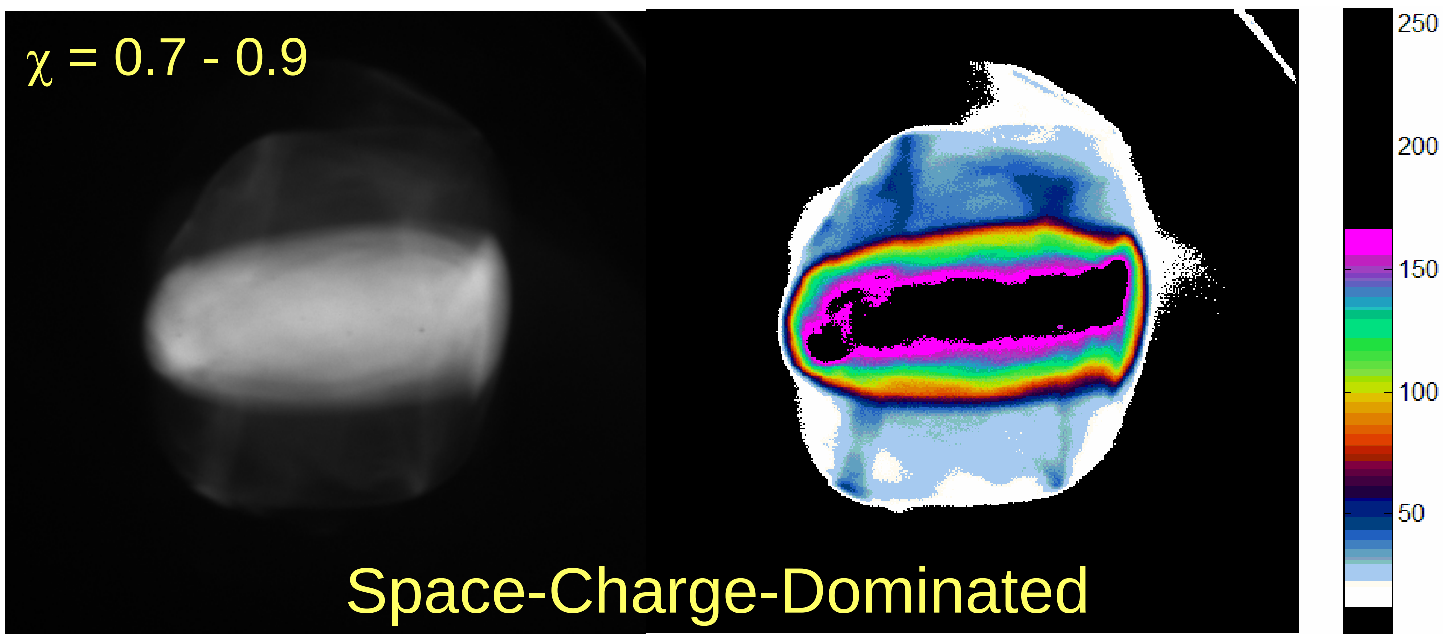
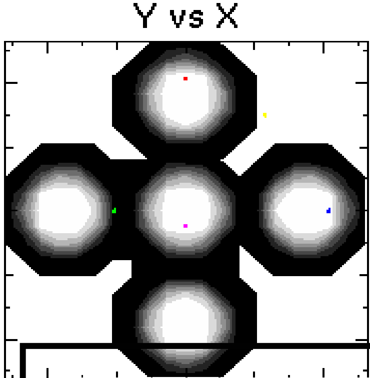


Photo credits:
UMER (Kishek, Stratakis)

Moral

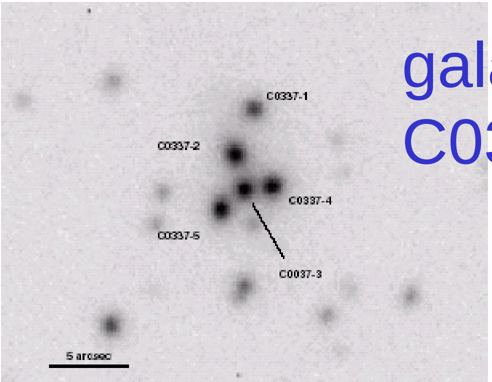
- No space charge: Motion depends on external forces (lattice)
- Space charge: Motion depends on the particle distribution itself, as well as on the external forces
  - Accurately measure the particle distribution – imaging and phase-space mapping diagnostics.
  - Model it correctly in simulation codes.
- Beams are born space-charge-dominated at the source
- In linacs, FELs, ERLs, machine is too short for beam to equilibrate: beam retains memory of its injected distribution



0.0 m

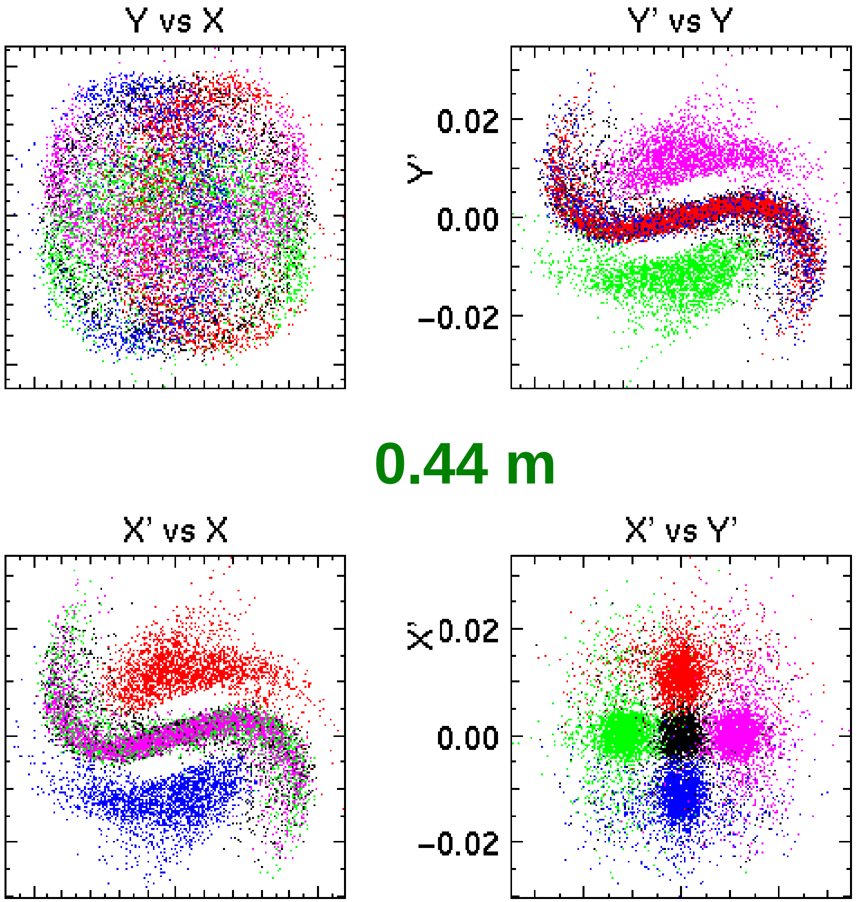
$\chi = 0.90$

Analogous to Merging Galaxies



galaxy cluster C0337-2522

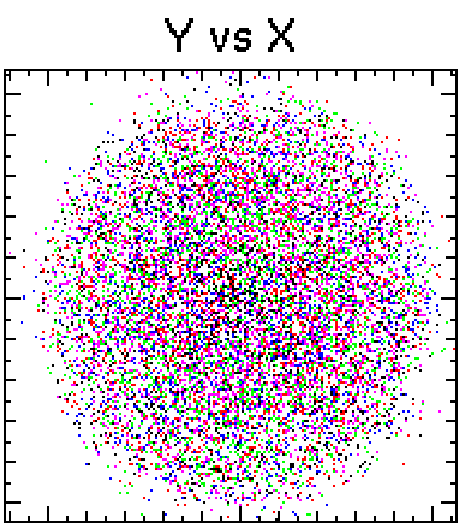
Credits: Nipoti, *et al.*, Mon. Not. R. Astron. Soc., **344**, 748-760 (2003).



0.44 m

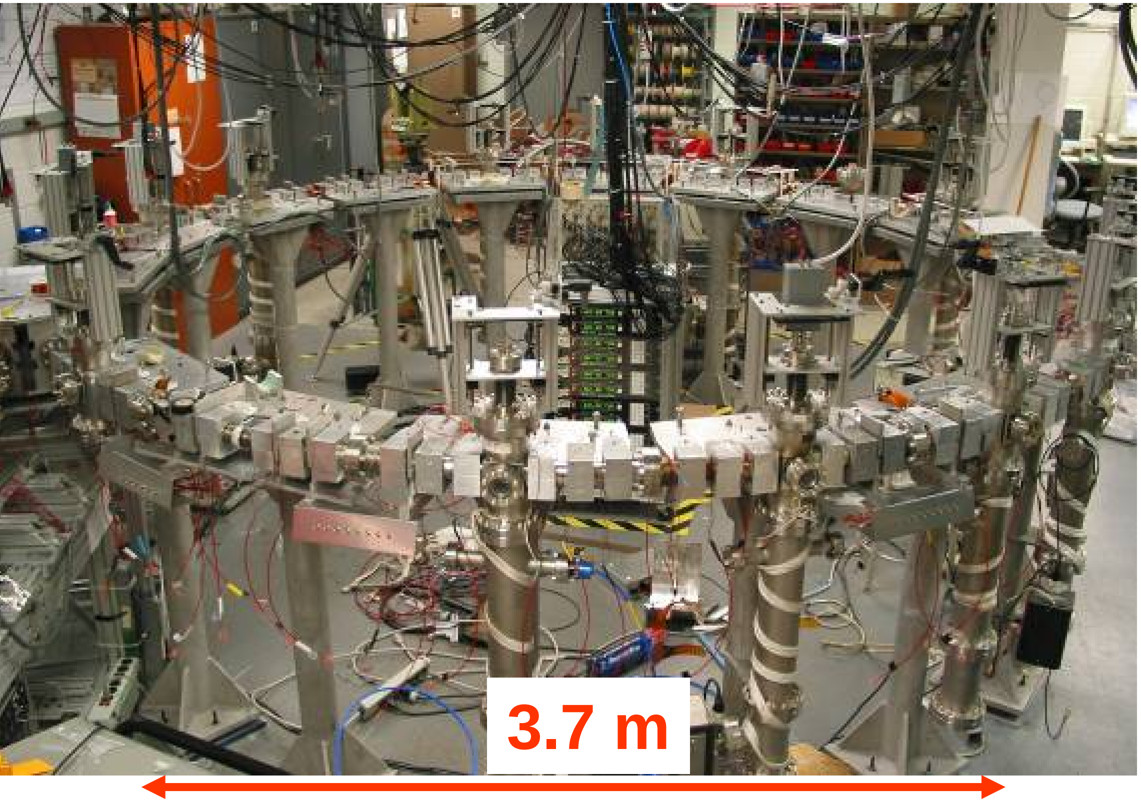
Memory of beamlets!

4.32 m

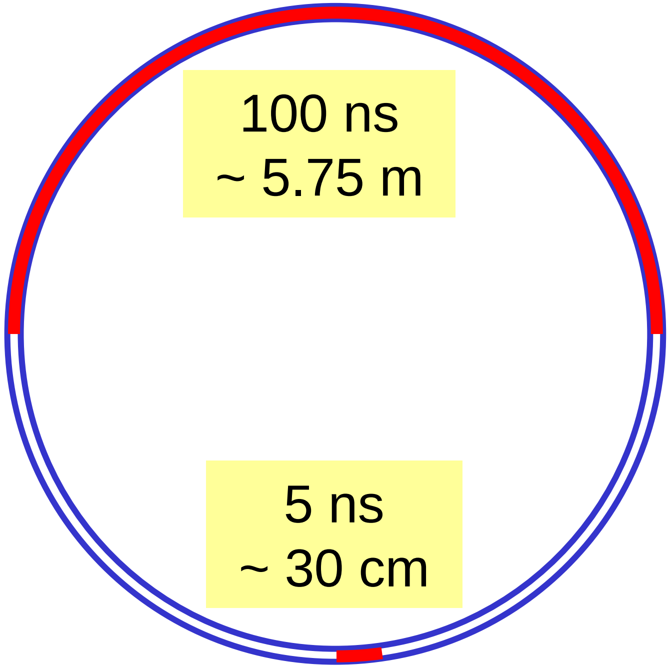


Finally, Complete Mixing

UMER – a Platform for Beam Dynamics Studies



Energy	**10 - 50 keV**
Current	**0.5-100 mA**
rms Emittance	**0.25-5 μm**



Scale model that is sufficiently complex

β comparable to 20-100 MeV/u ions

No radiation; inexpensive hardware; 10-15 G fields

UMER Construction funded by Office of Science U.S. DEPARTMENT OF ENERGY

UMER Research Goals

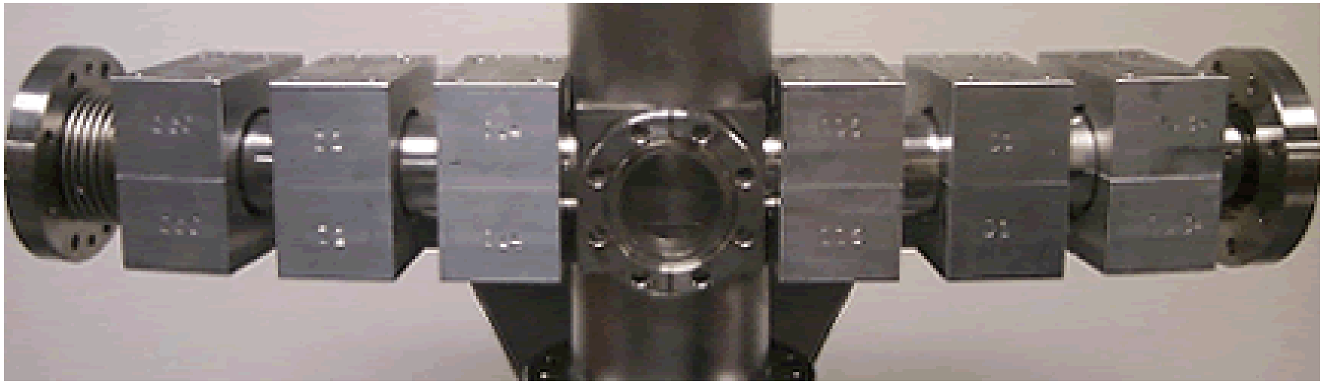
Platform to advance knowledge in accelerator and beam physics

Model space charge physics in:

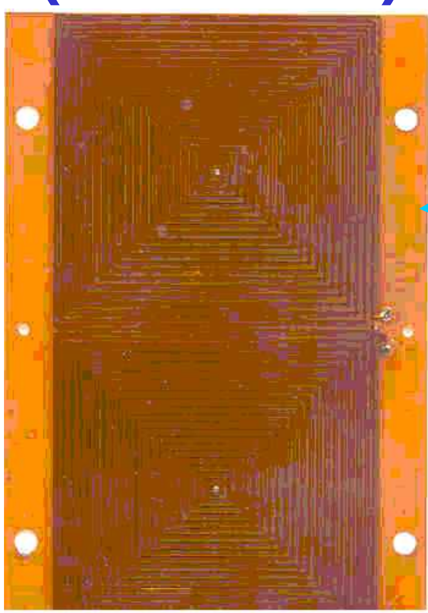
- proton machines (neutron sources, drivers for muon colliders)
- heavy ion beams (nuclear physics, inertial fusion)
- electron injectors (FELs, ERLs)

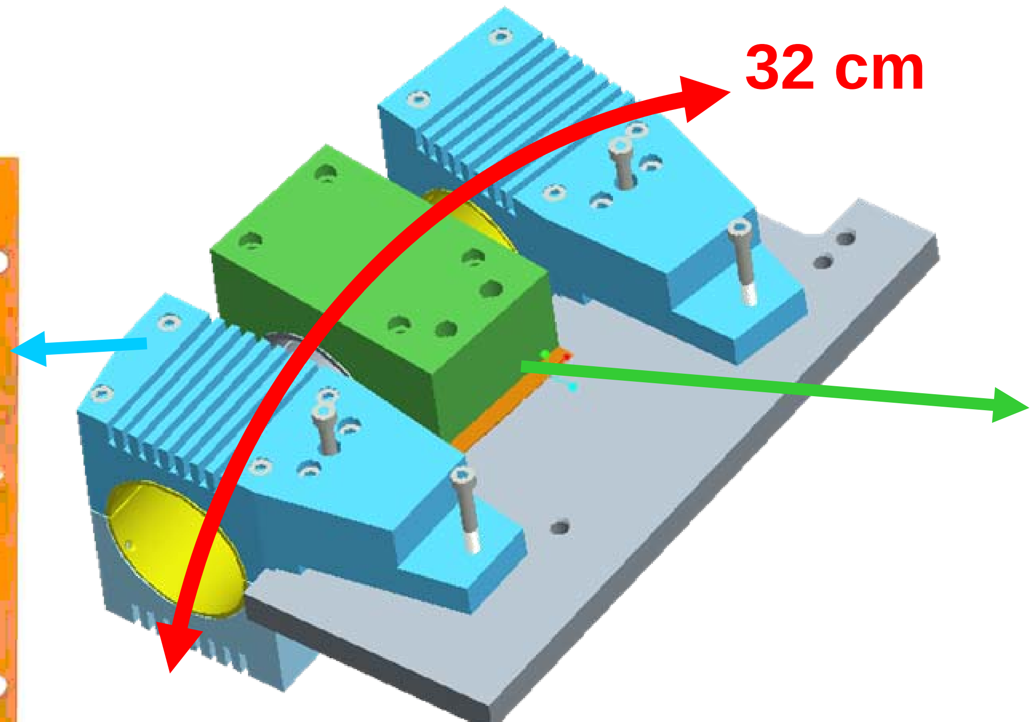
Ring Physics Resonances Dispersion	Linacs/FELs Halo Nonequilibrium Distributions
Transverse	Longitudinal
Little Space Charge	Intense Space Charge

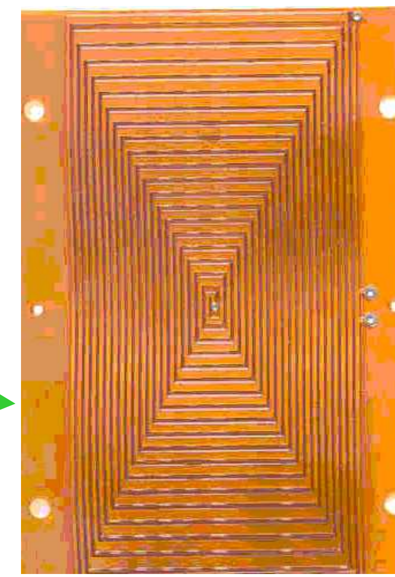
UMER Magnets & Lattice



72 Quads
(~ 7.8 G/cm)







36 Dipoles
(~ 15 G)

UMER Diagnostics

Imagers:

– Fluorescent Screen Imagers
– Optical Transition Radiation (OTR) Imagers
– Fast Fluorescent Screens

Phase-Space Mappers:

– Tomographic Magnet-scan (⊥)
– Fast (Slice) Tomography
– Slit-wire (⊥)
– Pepper-pot (⊥)
– Fast Retarding Potential Energy analyzers (//)

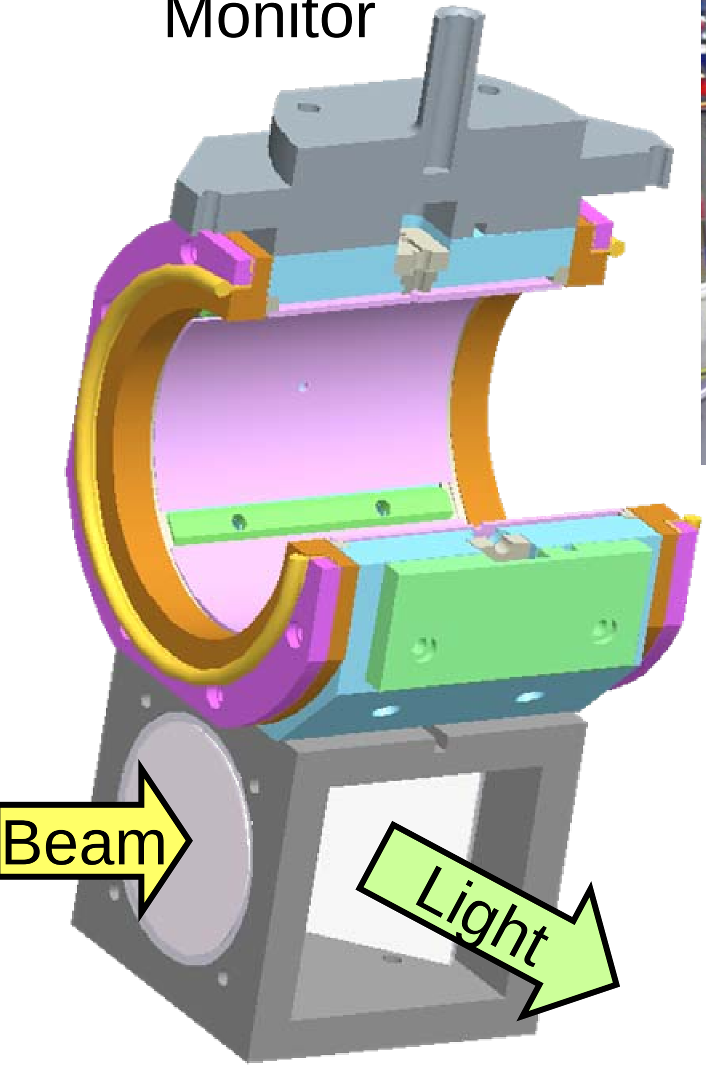
Beam pickups:

– Rogowski Coils
– Bergoz Current Monitors
– Wall-Current Monitors
– Fast Capacitive Beam Position Monitors

Fast = 3-5 ns resolution

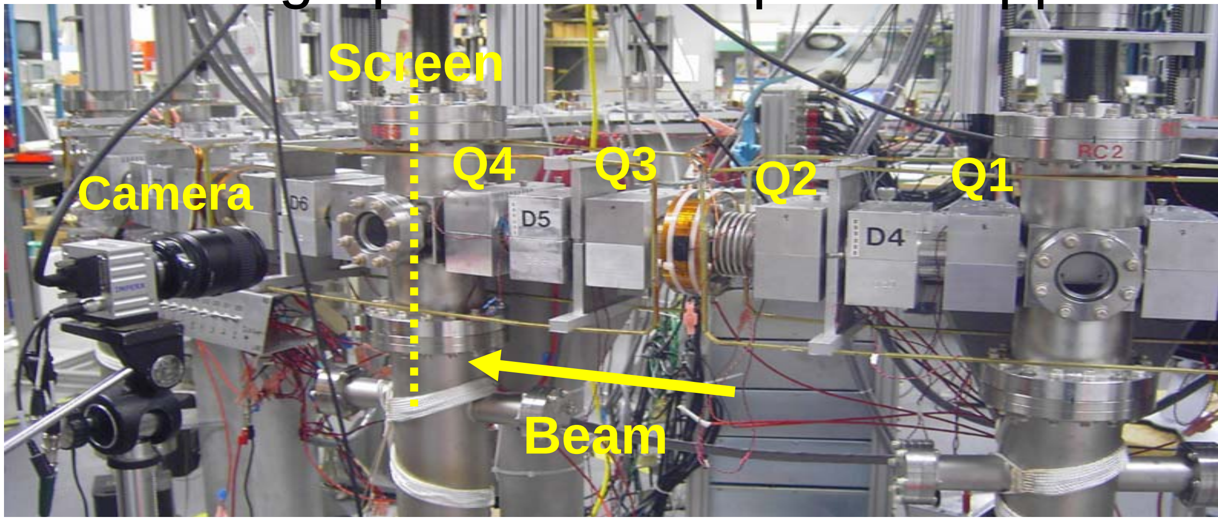
UMER Phase Space Diagnostics

Beam Position Monitor

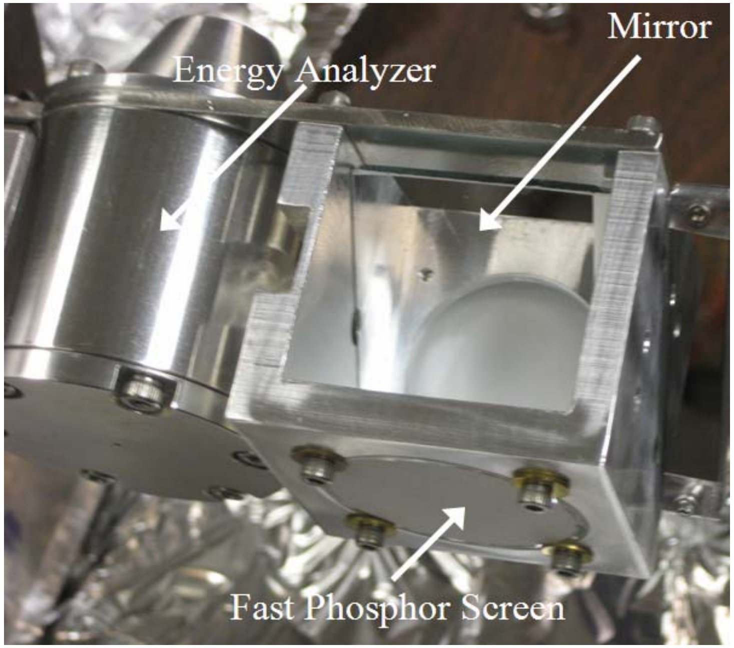


Fluorescent Screen

Tomographic Phase-Space Mapper



Energy Analyzer



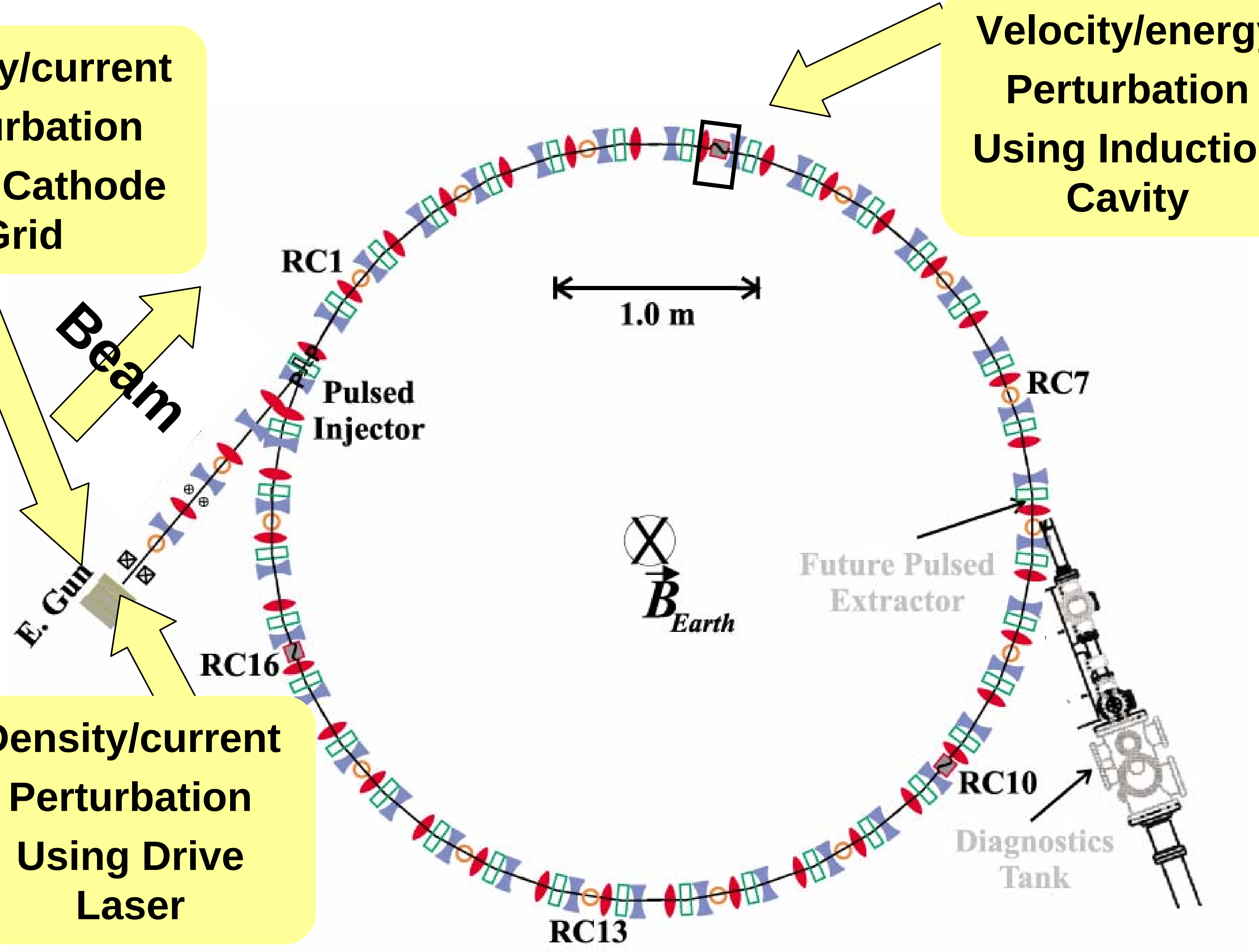
Fast Fluorescent Screen

Deliberate Modulation of Beam Density or Energy

Density/current Perturbation Using Cathode Grid

Velocity/energy Perturbation Using Induction Cavity

Density/current Perturbation Using Drive Laser



Simulation codes we use to build understanding

1. WARP – particle-in-cell accelerator code, self-consistent
2. WinAgile – single-particle matrix code for rings
3. ELEGANT – widely-used single-particle code,
   with option to add space charge
4. COSY Infinity – single-particle matrix code
5. Envelope codes (TRACE, PBOLab, SPOT, MEnv)
6. 1-D fluid code for longitudinal dynamics

Additional Codes – You will be using these here

1. Image processing codes:
   - PhotoProcess.m
   - Image-J

2. Tomographic reconstruction code

3. Longitudinal code: end erosion