Longitudinal Beam Physics on UMER

Patrick O'Shea and the UMER Team
June 23, 2008

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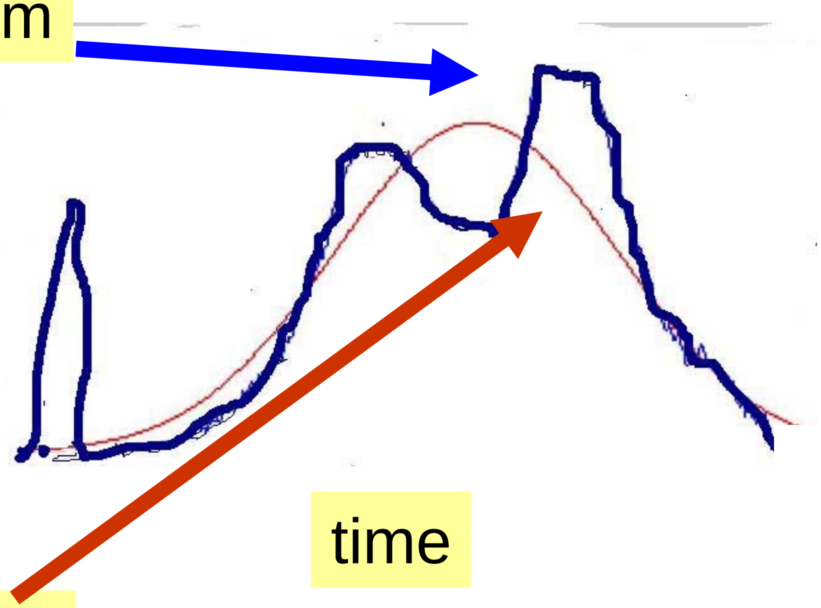
Outline

- Importance of longitudinal structure
- Some gun physics
- Launching waves
- Speed of sound
- Beam transport

Real electron beam distributions are not named after famous people!



Real beam

current

Longitudinal (time) structure

time

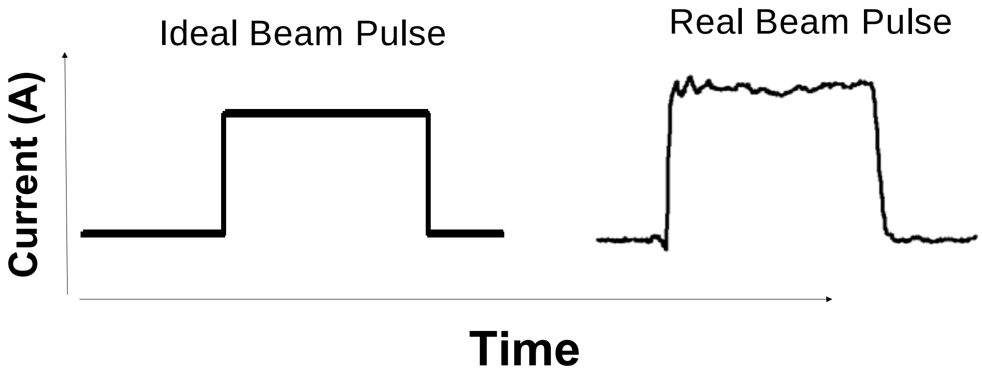
Gaussian beam

Real beam = Asymmetric Bactrian Camel with Attendant Obelisk Distribution

Problem Statement

Problem:

Real beams have unwanted velocity (energy) or density modulations



Reasons:

- Drive laser fluctuations in photoinjectors
- Over-focusing or under-focusing in longitudinal focusing systems

Technique:

- Introduce perturbation "deliberately" in an intense beam and study its evolution.

- UMER provides the platform for such experiments

Sources of problems

Causal connection

What	Where	How
Space charge (self) fields	electron source, low energy injector/linac,	Space charge converts density modulation to energy modulations, and causes time dependant defocusing
Wakefields/Higher OM	Cavities and structures	Bunch structure can excite high frequency modes
Coherent Synchrotron Radiation (CSR)	bends	Bunch structure can excite coherent synchrotron radiation

Two Types of Longitudinal Problems on UMER

- Longitudinal effects in the gun and space charge driven instabilities
- Longitudinal effects in in multi-turn transport: evolution of perturbations

These are relevant to other accelerators

1. Longitudinal structure and space charge instabilities in the gun

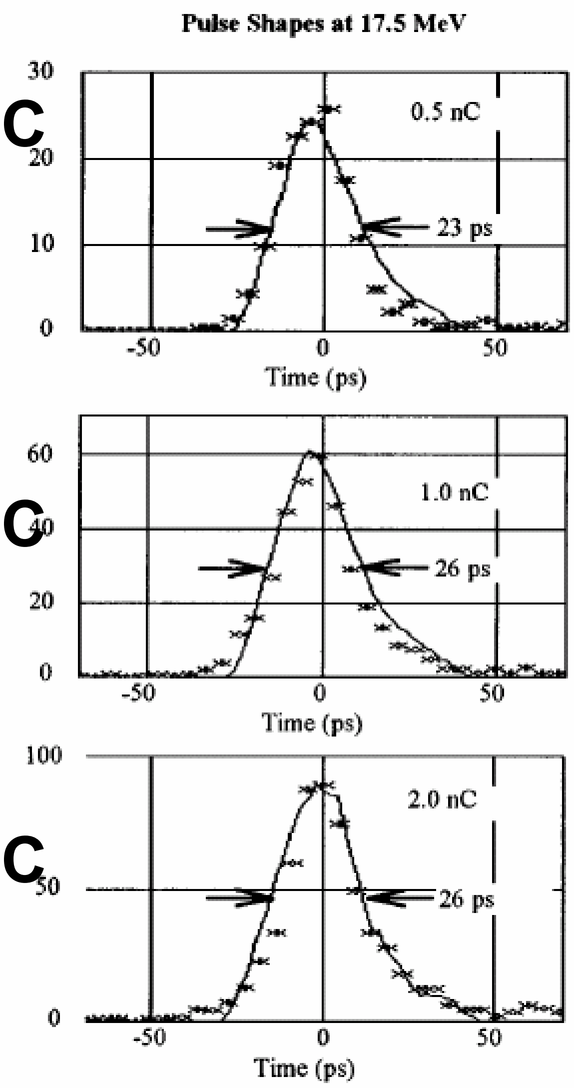
Space-charge driven longitudinal beam breakup

D.H Dowell et al. Phys Plasmas, 4, 3369 (1997)

0.5 nC

1.0 nC

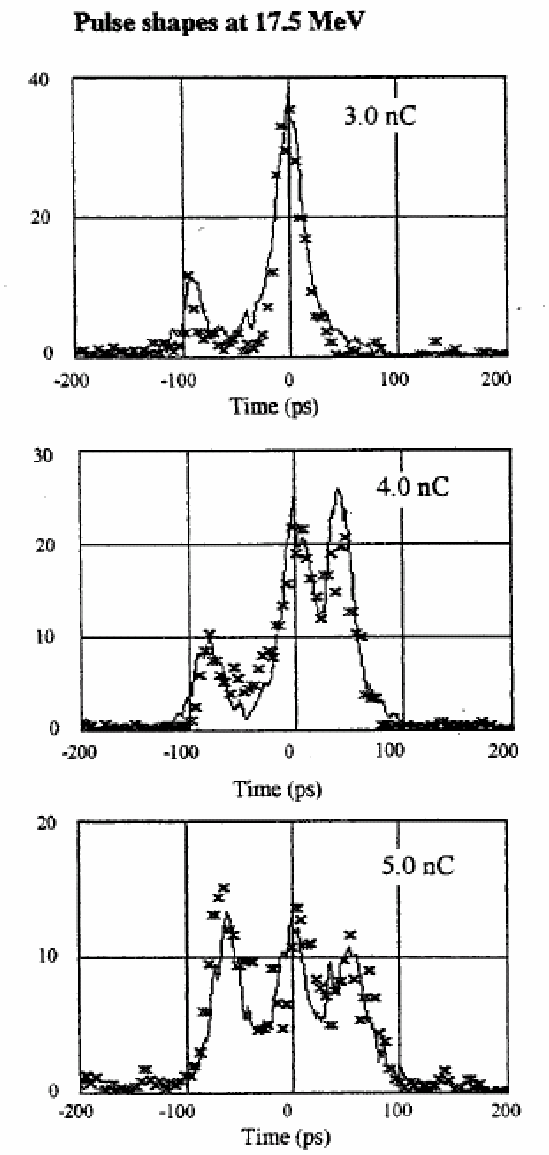
2.0 nC



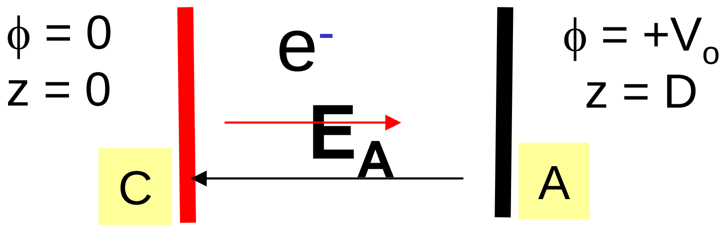
3 nC

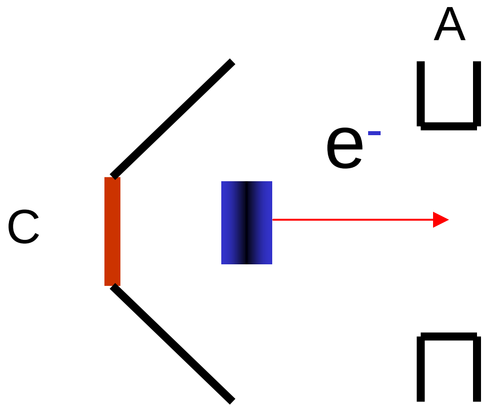
4 nC

5 nC



Child- Langmuir Limit Revisited





Conventional Child-Langmuir Analysis:
Uniform 1-D current distribution
Steady state
Pulse length τ_p >> Electron transit time T

Real Photoinjector Analysis:
non-uniform 3-D time-dependant current distribution
transient state
Pulse length τ_p < Electron transit time T

Cathode – Anode Transit Time (T) in guns

Non-relativistic

$$T = \sqrt{\frac{2D^2 m}{eV_0}}$$

$D = A/C$ gap $= 2.5$ cm in UMER

$V_0 =$ Gun voltage $= 10$ kV

For UMER gun $T \approx 1$ ns

Relativistic

$$T = \frac{mc\gamma_f \sqrt{1 - \frac{1}{\gamma_f^2}}}{eE_A}$$

$\gamma_f =$ relativistic factor at gun exit $\approx$ 3 for 1 MeV

$E_A =$ average applied electric field $\approx$ 30 MV

For Relativistic gun $T \approx .15$ ns

For a typical RF photoinjector $\tau_p \approx 0.01$ ns

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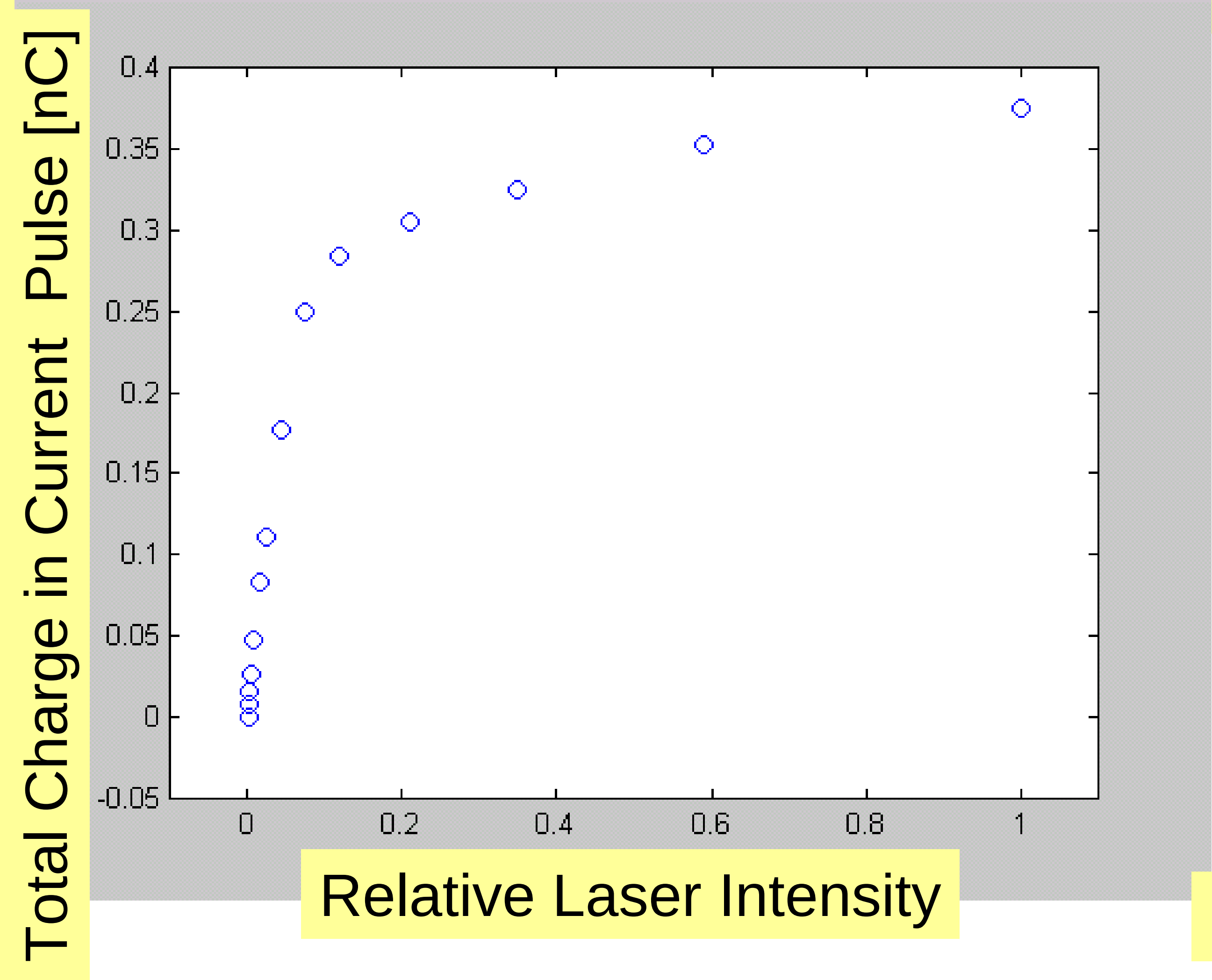
Charge per Pulse vs Drive Laser Intensity
Experimental data



5-kV gun

Ágúst Valfells, D. W. Feldman, M. Virgo, P. G. O'Shea, and Y. Y. Lau, “Effects of pulse-length and emitter area on virtual cathode formation in electron guns”, *Phys. Plasmas* **9**, 2377 (2002)

Critical Current (J_{crit}) in short pulse mode for onset of space charge instabilities

Critical current density:

$$J_{CRIT} = 2\frac{1-\sqrt{1-\frac{3}{4}X_t^2}}{X_t^3}J_{CL}$$

$$X_t = \tau_p / \mathrm{T}$$

Critical charge density:

$$Q_{CRIT} = 2\frac{1-\sqrt{1-\frac{3}{4}X_t^2}}{X_t^2}Q_{CL}$$

Short pulse mode $X_t << 1$

$$J_{CRIT} \approx \frac{3}{4X_t}J_{CL}$$

$$Q_{CRIT} \approx \frac{3}{4}Q_{CL}$$

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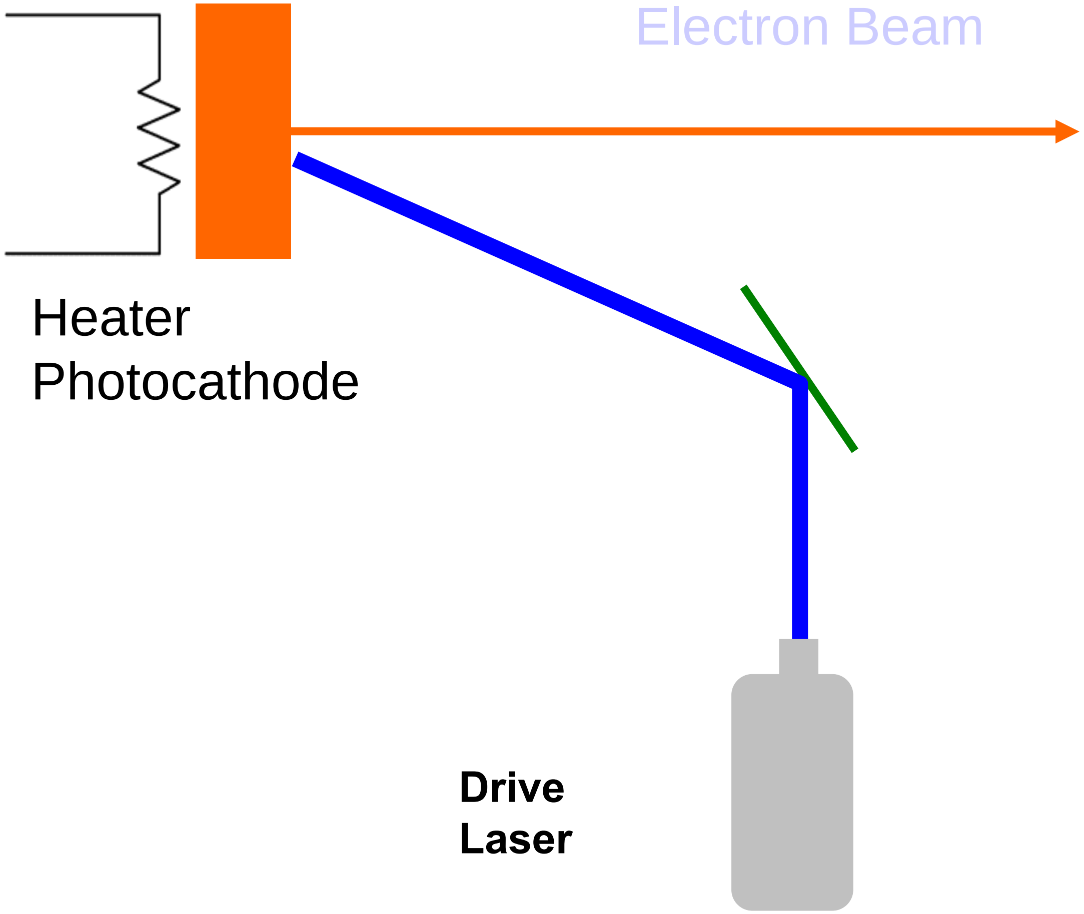
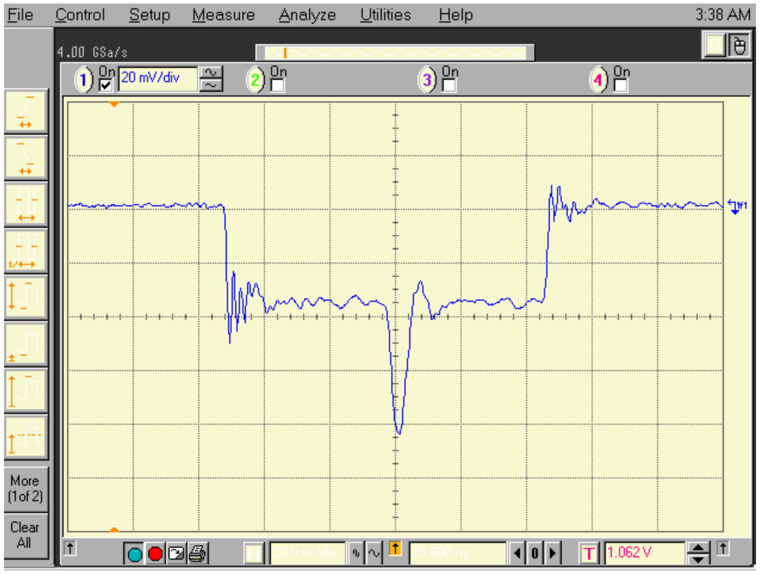
Ágúst Valfells, D. W. Feldman, M. Virgo, P. G. O'Shea, and Y. Y. Lau, "Effects of pulse-length and emitter area on virtual cathode formation in electron guns", *Phys. Plasmas* **9**, 2377 (2002)

UMER is a unique test bed for studying the evolution of current perturbations





Thermionic only; 100ns pulse

Thermionic + Photoemission (5ns pulse)

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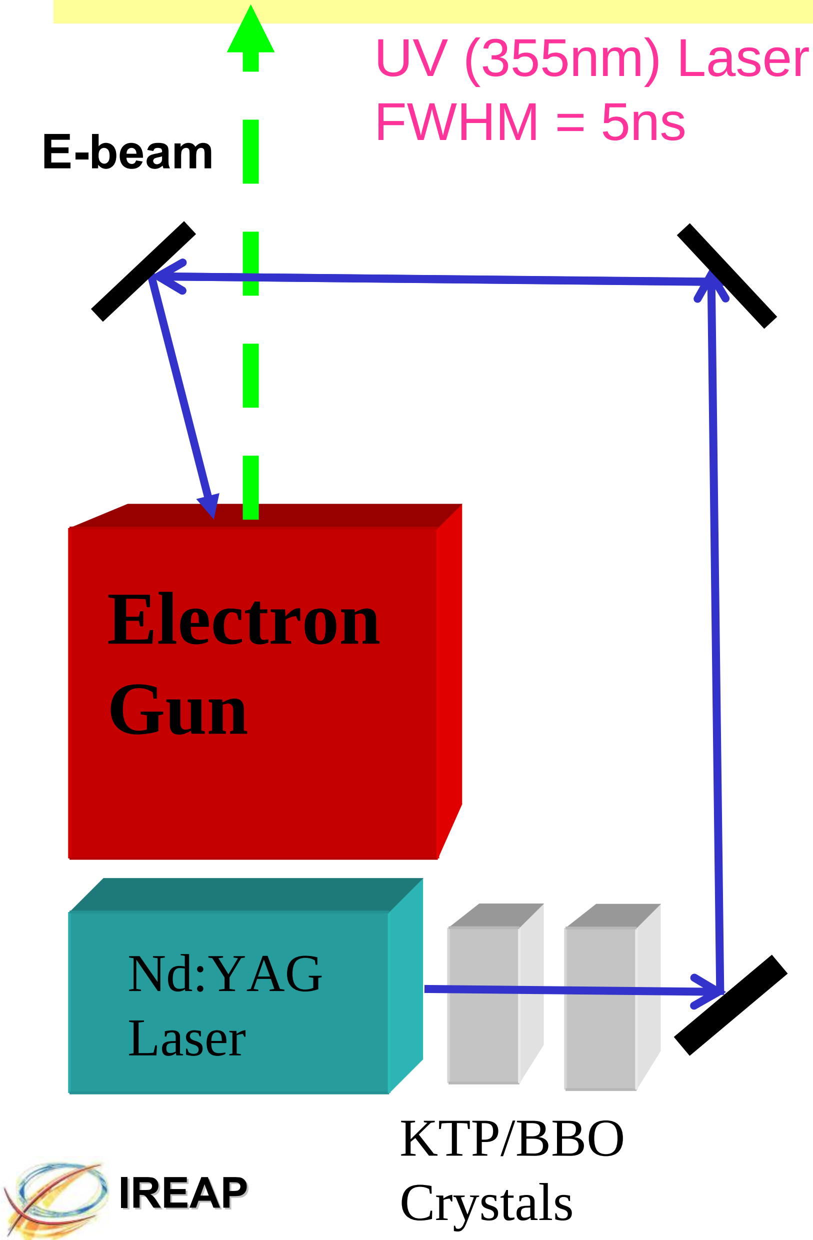
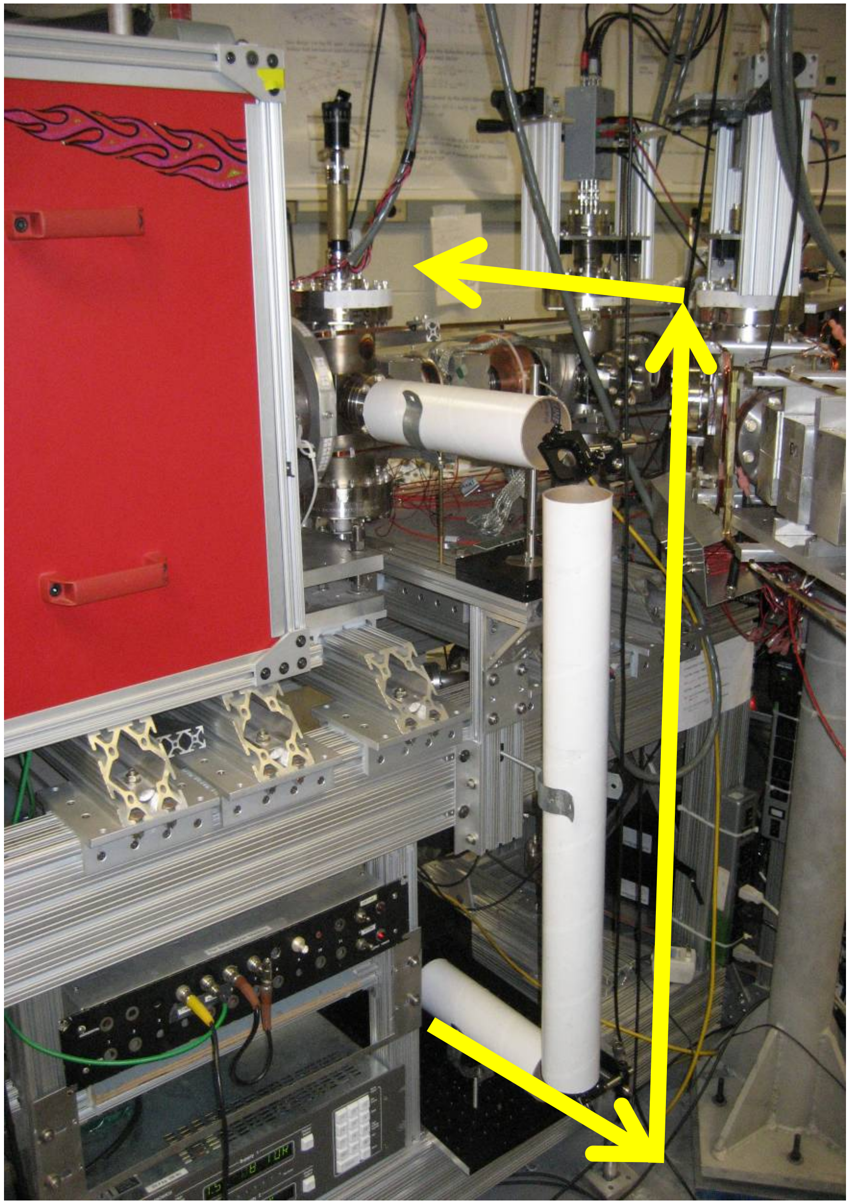
UMER Drive Laser Setup





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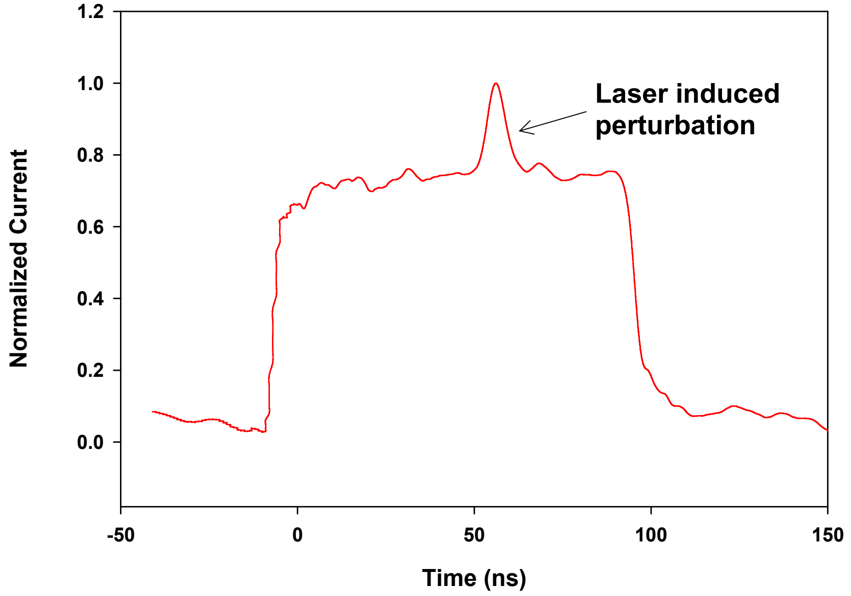
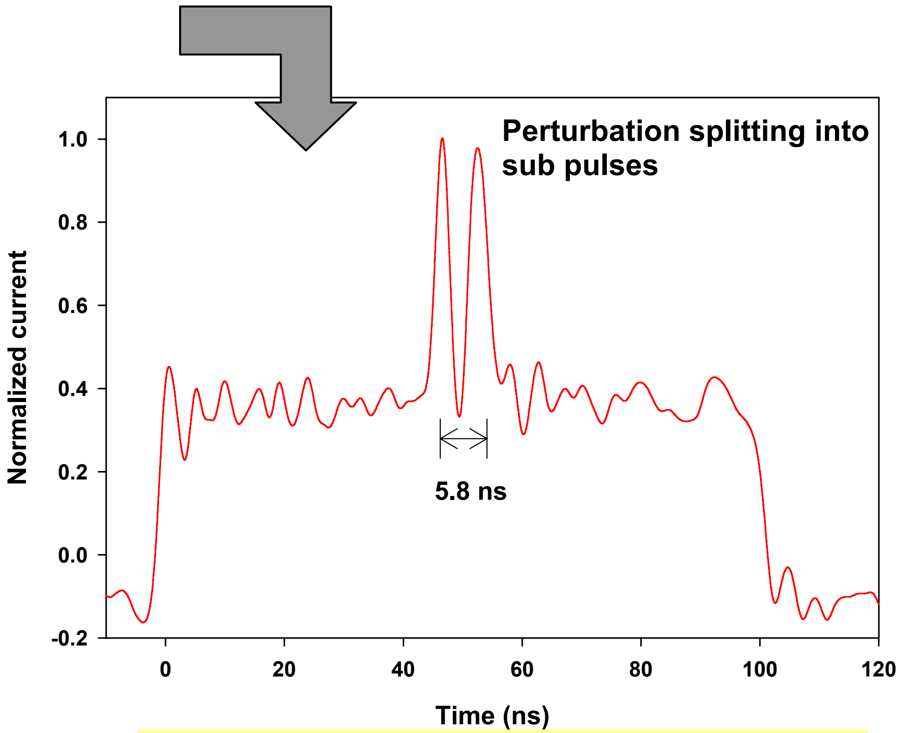
Space Charge Instabilities in the UMER Gun



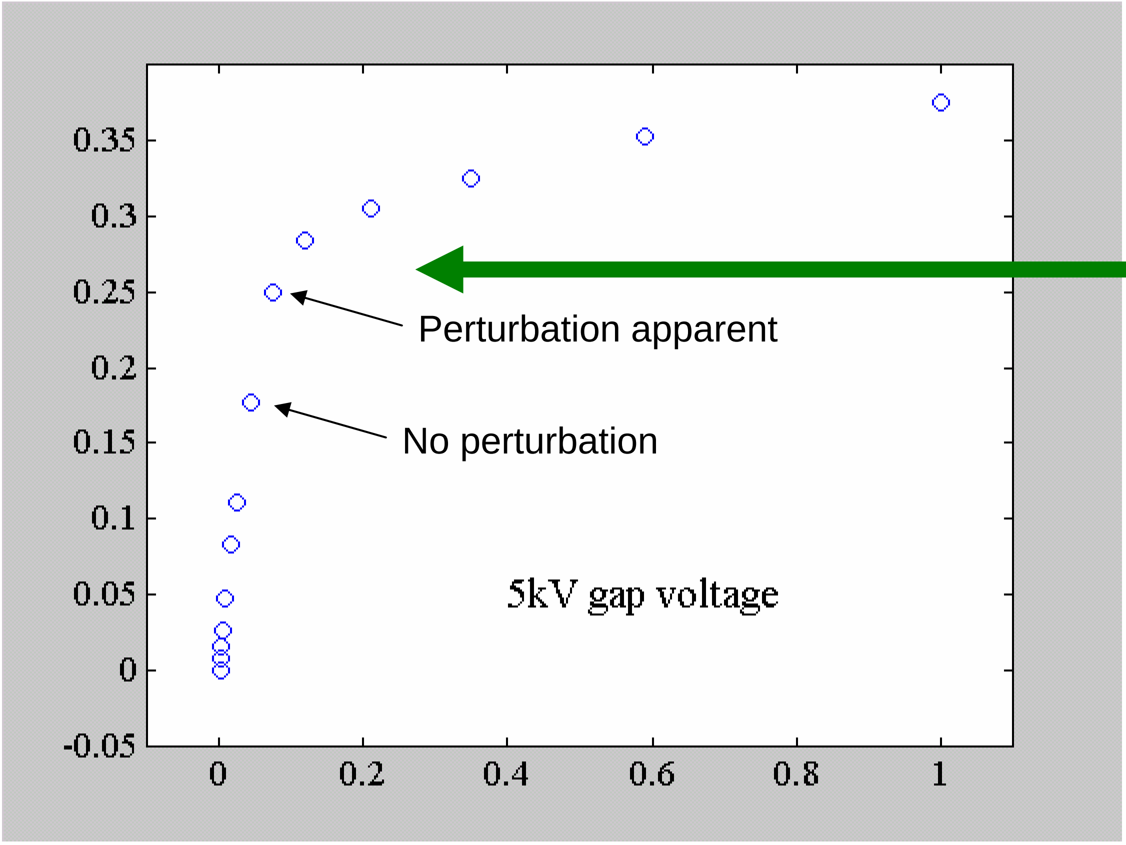
Perturbation **below** the critical current density

At large laser power



Perturbation **above** the critical current density

Charge per pulse vs laser intensity
Onset of longitudinal instability
Experimental data



Total Charge in Current Pulse [nC]

Relative Laser Intensity

$$Q_{CRIT} \approx \frac{3}{4} Q_{CL}$$

Ágúst Valfells, D. W. Feldman, M. Virgo, P. G. O'Shea, and Y. Y. Lau, “Effects of pulse-length and emitter area on virtual cathode formation in electron guns”, *Phys. Plasmas* **9**, 2377 (2002)

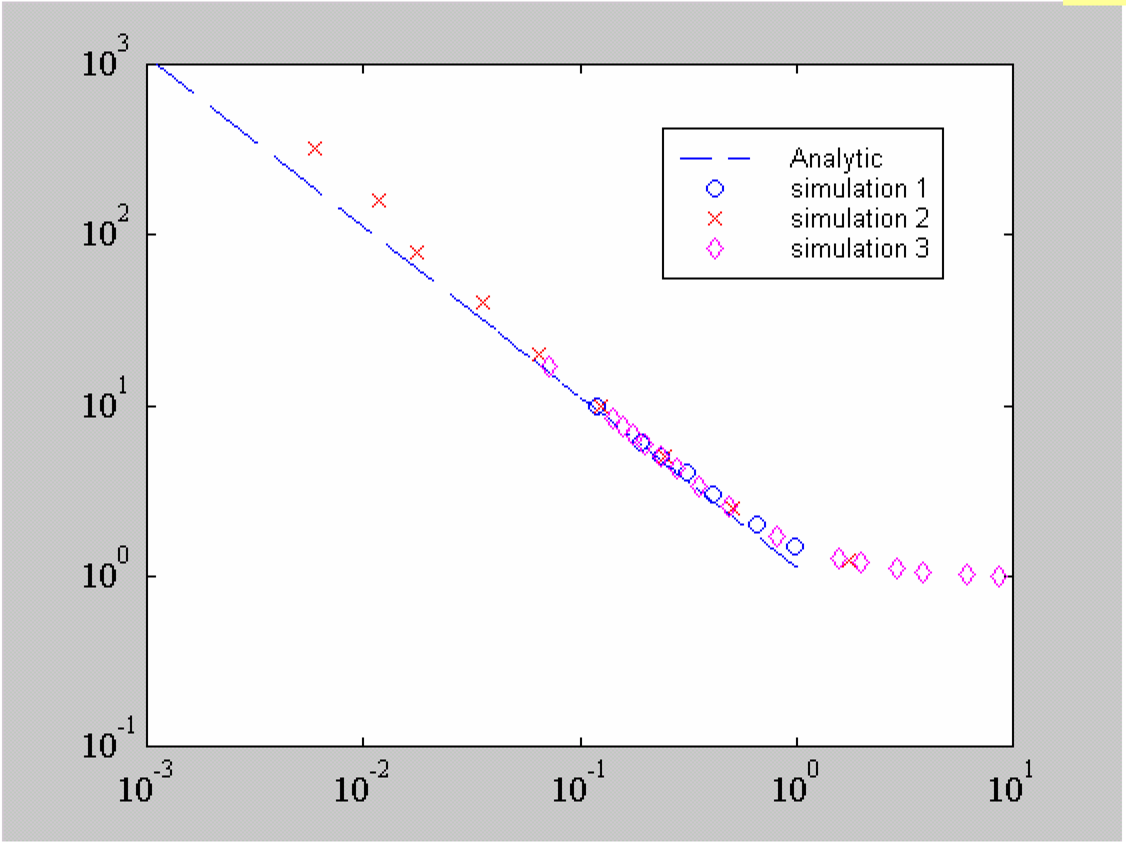
Critical Current Density vs. pulse length

Simulation

$$J_{CRIT} = 2\frac{1-\sqrt{1-\frac{3}{4}X_t^2}}{X_t^3}J_{CL}$$

$$X_t = \tau_p / \mathrm{T}$$

Normalized Current Density (J_{crit}/J_{CL})

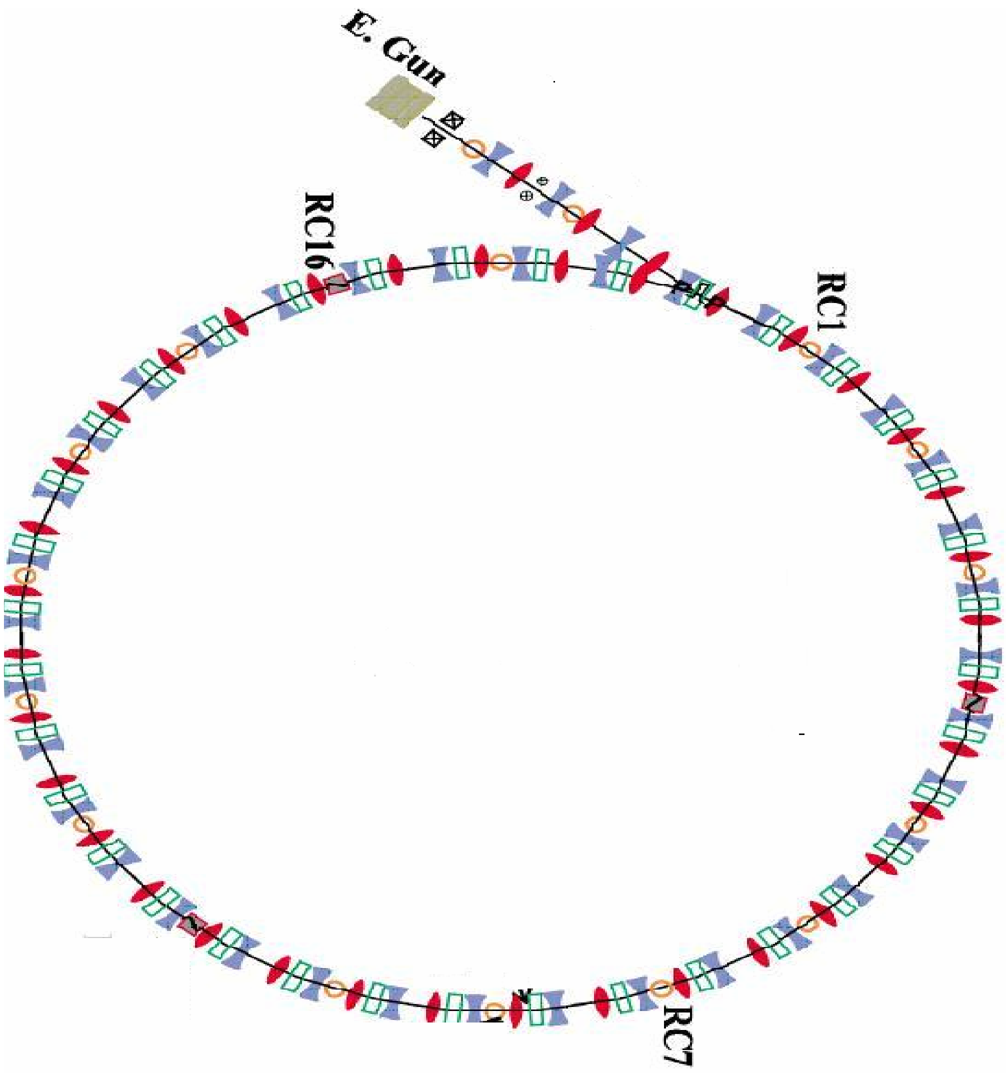


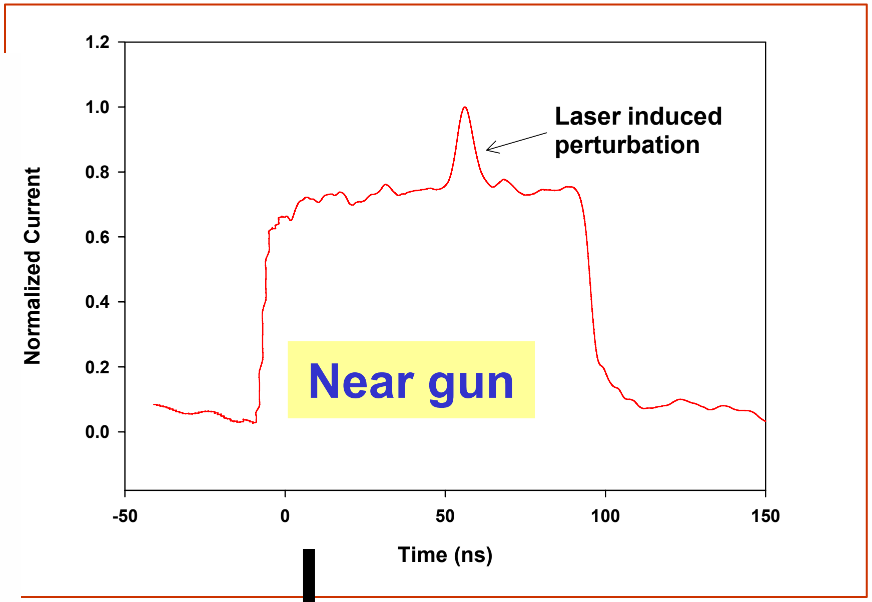
Normalized Pulse Length [$\tau_p/T_{transit}$]

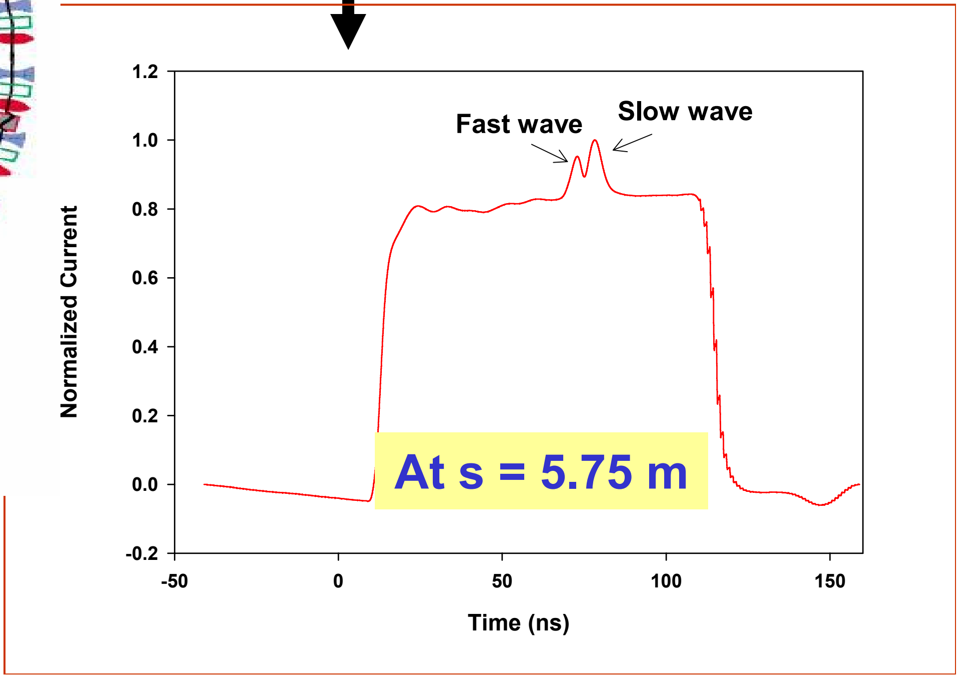
Ágúst Valfells, D. W. Feldman, M. Virgo, P. G. O'Shea, and Y. Y. Lau, “Effects of pulse-length and emitter area on virtual cathode formation in electron guns”, *Phys. Plasmas* **9**, 2377 (2002)

2. Evolution of longitudinal structure in beam transport

Experimental Results of Laser-induced Space Charge waves







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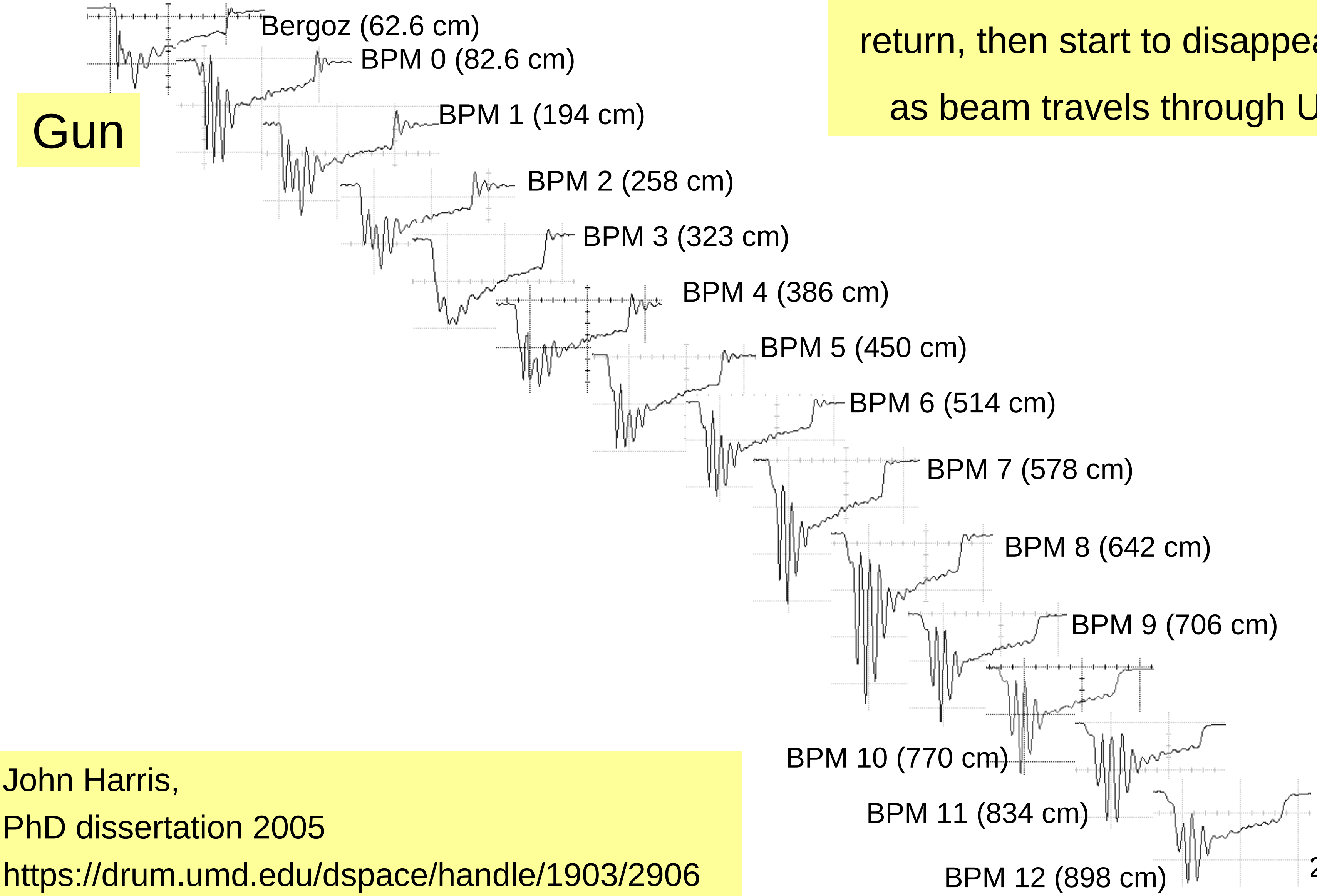
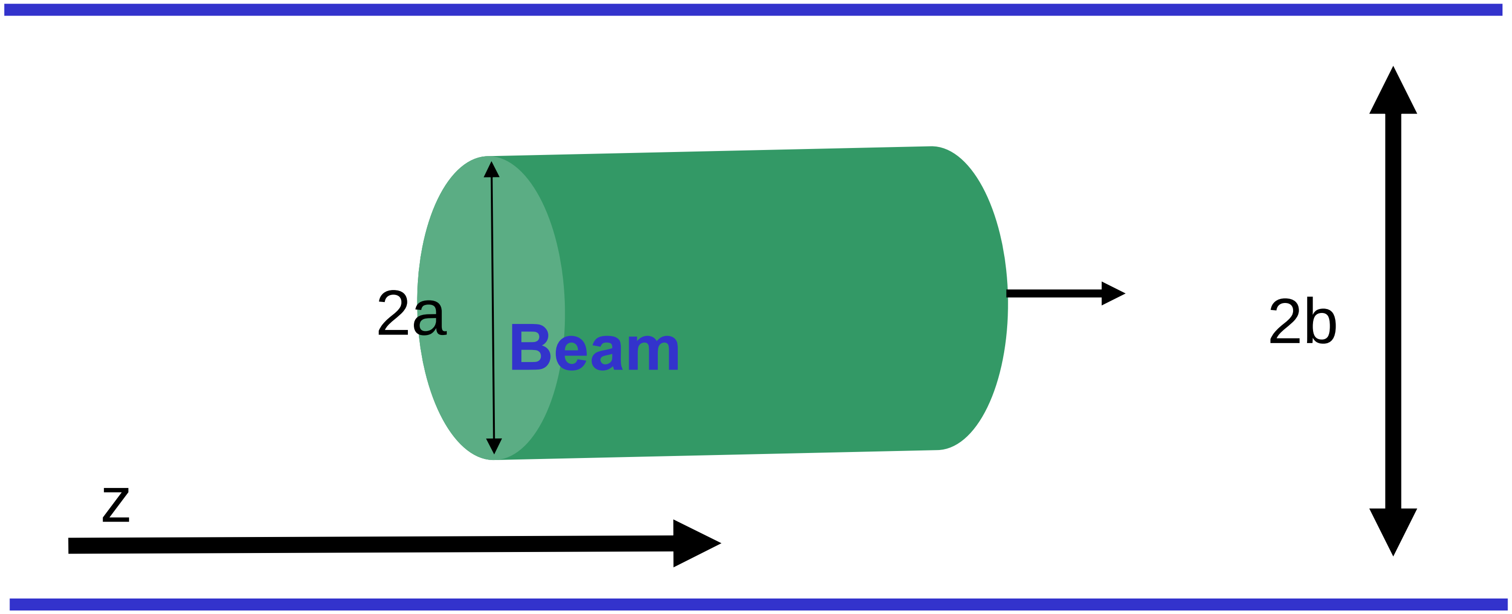
Evolution of Multiple Pulses

Modulation observed to disappear, return, then start to disappear again as beam travels through UMER



John Harris,
PhD dissertation 2005
https://drum.umd.edu/dspace/handle/1903/2906

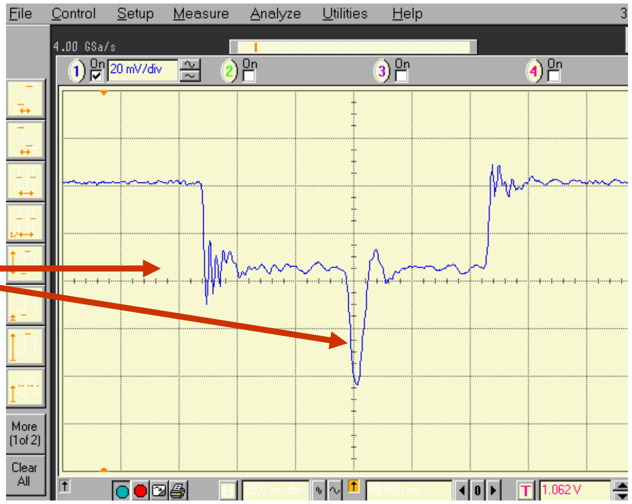
Theory of Space Charge Waves
(1-D Cold fluid model)



Space charge line density $\Lambda(z,t) = \Lambda_0 + \Lambda_1 e^{i(\omega t - kz)}$

Velocity $\mathrm{v}(z,t) = \mathrm{v}_0 + \mathrm{v}_1 e^{i(\omega t - kz)}$

Current $I(z,t) = I_0 + I_1 e^{i(\omega t - kz)}$



Derivation of Sound Speed

(one-dimension cold-fluid model)

Definition of perturbation

$$\begin{cases} \Lambda(z,t) = \Lambda_0 + \Lambda_1 e^{i(\omega t - kz)} \\ \mathrm{v}(z,t) = \mathrm{v}_0 + \mathrm{v}_1 e^{i(\omega t - kz)} \\ I(z,t) = I_0 + I_1 e^{i(\omega t - kz)} \end{cases}$$

Continuity equation

Momentum equation

$$\begin{cases} \dfrac{\partial(\Lambda \mathrm{v})}{\partial z} + \dfrac{\partial \Lambda}{\partial t} = 0 \\ \dfrac{\partial \mathrm{v}}{\partial z}\mathrm{v}_0 + \dfrac{\partial \mathrm{v}}{\partial t} = \dfrac{q}{\gamma_0^3 m} E_s \end{cases}$$

Maxwell's equation and boundary conditions

$$E_s = -\frac{g}{4\pi\varepsilon_0}\left(\frac{\partial \Lambda}{\partial z} + \frac{1}{c^2}\frac{\partial I}{\partial t}\right)$$

$$g = 2\ln\frac{b}{a}$$

Dispersion equation

$$\boxed{(\omega - k\mathrm{v}_0)^2 - C_s^2 k^2 = 0}$$

C_s = Sound speed

Phase velocity of fast/slow waves

$$\mathrm{v}_f = \frac{\omega}{k_+} = \mathrm{v}_0 + C_s$$

$$\mathrm{v}_s = \frac{\omega}{k_+} = \mathrm{v}_0 - C_s$$

$$C_s = \sqrt{\frac{qg\Lambda_0}{4\pi\varepsilon_0\gamma_0^5 m}}$$

$$or\ C_s = \sqrt{\frac{egI}{4\pi\varepsilon_o m v_o \gamma^5}}$$

For UMER $C_s \approx 10^6$ m/s

M. Reiser, Theory and Design of Charged Particle Beams, Chapter 6, (2008)

Evolution of Space-Charge Waves
Fast (Forward) and Slow (Backward) Waves

Definition of perturbation

$$\begin{cases} \mathrm{v}_1(0,t) = \delta \mathrm{v}_0\, p(t) \\ I_1(0,t) = \eta I_0\, p(t) \\ \Lambda_1(0,t) = (\eta - \delta)\Lambda_0\, p(t) \end{cases}$$

Algebraic equations of

Assume pure density perturbation $\delta = 0$

$$\Lambda_1(z,t) = \frac{\Lambda_0}{2}\eta\left[h\left(t - \frac{z}{\mathrm{v}_0 - C_s}\right) + h\left(t - \frac{z}{\mathrm{v}_0 + C_s}\right)\right]$$

$$\mathrm{v}_1(z,t) = \frac{C_s}{2}\eta\left[-h\left(t - \frac{z}{\mathrm{v}_0 - C_s}\right) + h\left(t - \frac{z}{\mathrm{v}_0 + C_s}\right)\right]$$

Red = slow (backward) wave
Blue = fast (forward) wave)

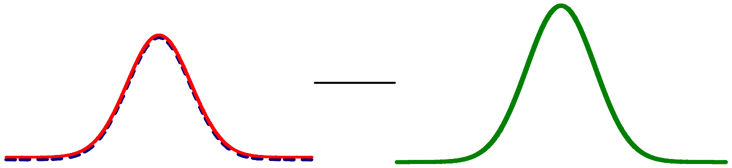
h function is a wave that depends of the initial conditions etc.

Evolution of Space-Charge Waves

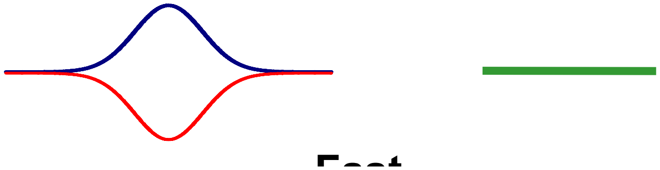
$$\Lambda_1(z,t)=\frac{\Lambda_0}{2}\eta\left[h\left(t-\frac{z}{\mathrm{v}_0-C_s}\right)+h\left(t-\frac{z}{\mathrm{v}_0+C_s}\right)\right]$$

$$\mathrm{v}_1(z,t)=\frac{C_s}{2}\eta\left[-h\left(t-\frac{z}{\mathrm{v}_0-C_s}\right)+h\left(t-\frac{z}{\mathrm{v}_0+C_s}\right)\right]$$

Line Charge Density – (Λ_1)



Velocity – (v_1)



Space Charge Wave Transport Experimental Results from UMER

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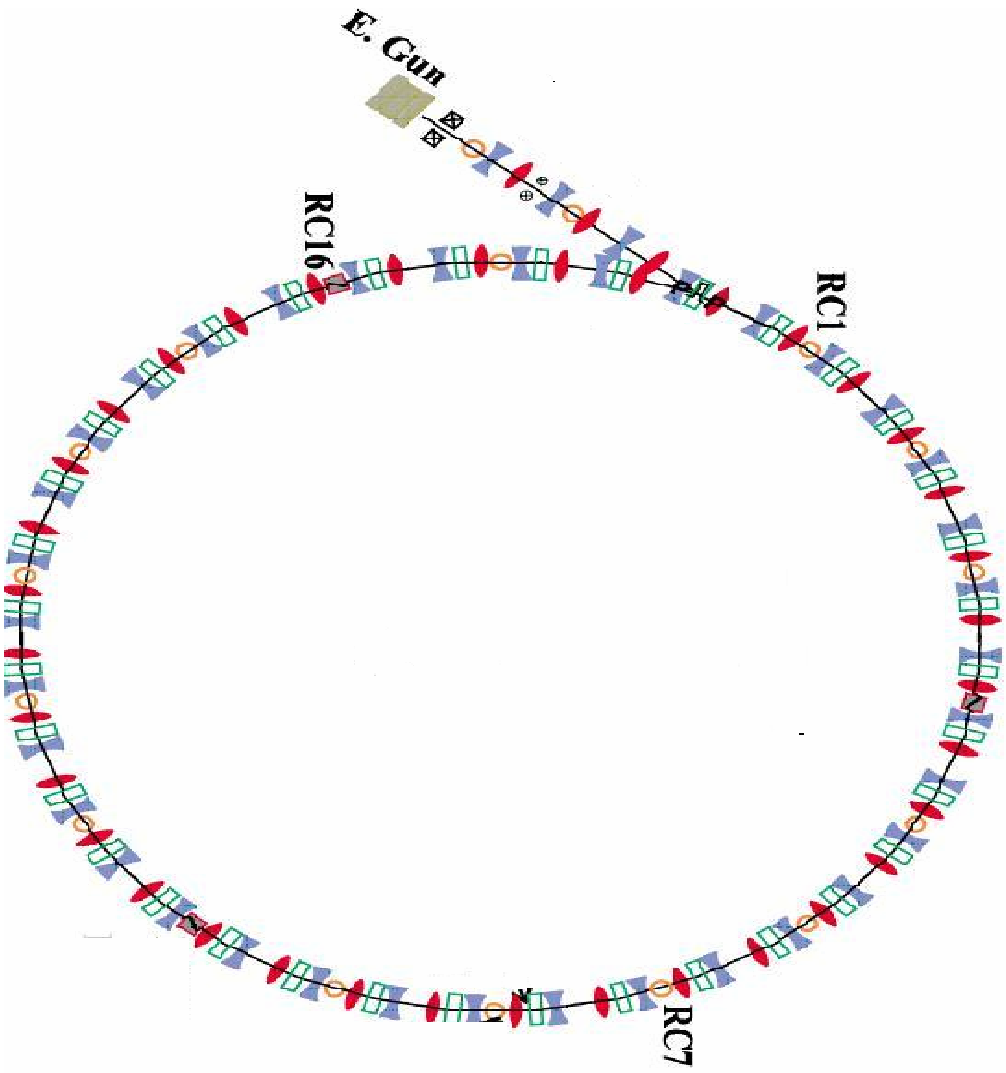
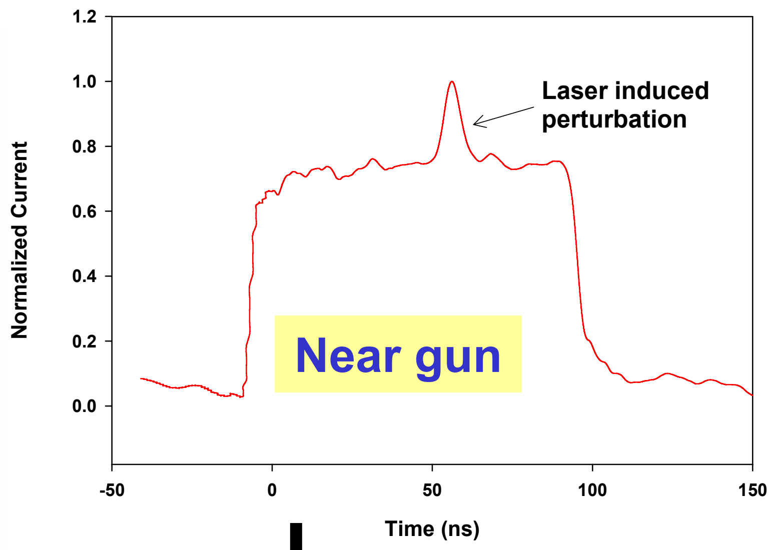
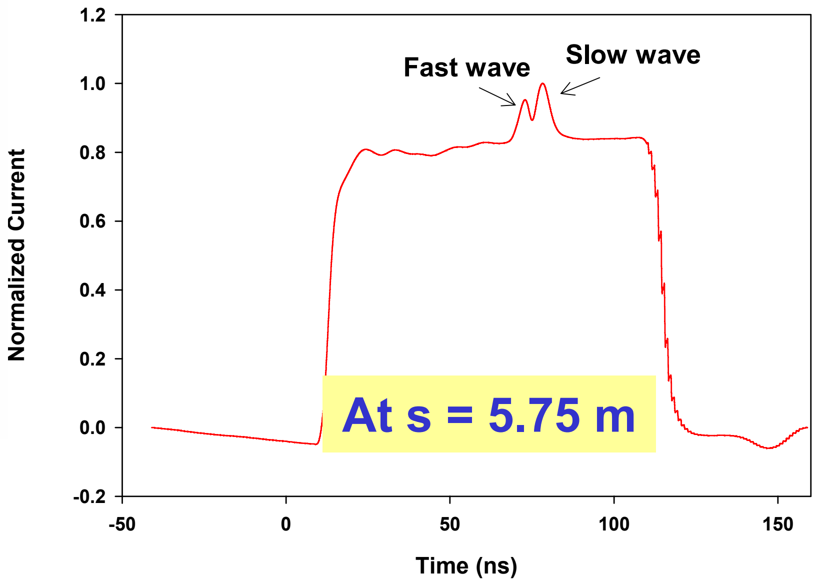
Experimental Results of Laser-induced Space Charge waves



C_s (theory) = $1.30*10^6$ m/s





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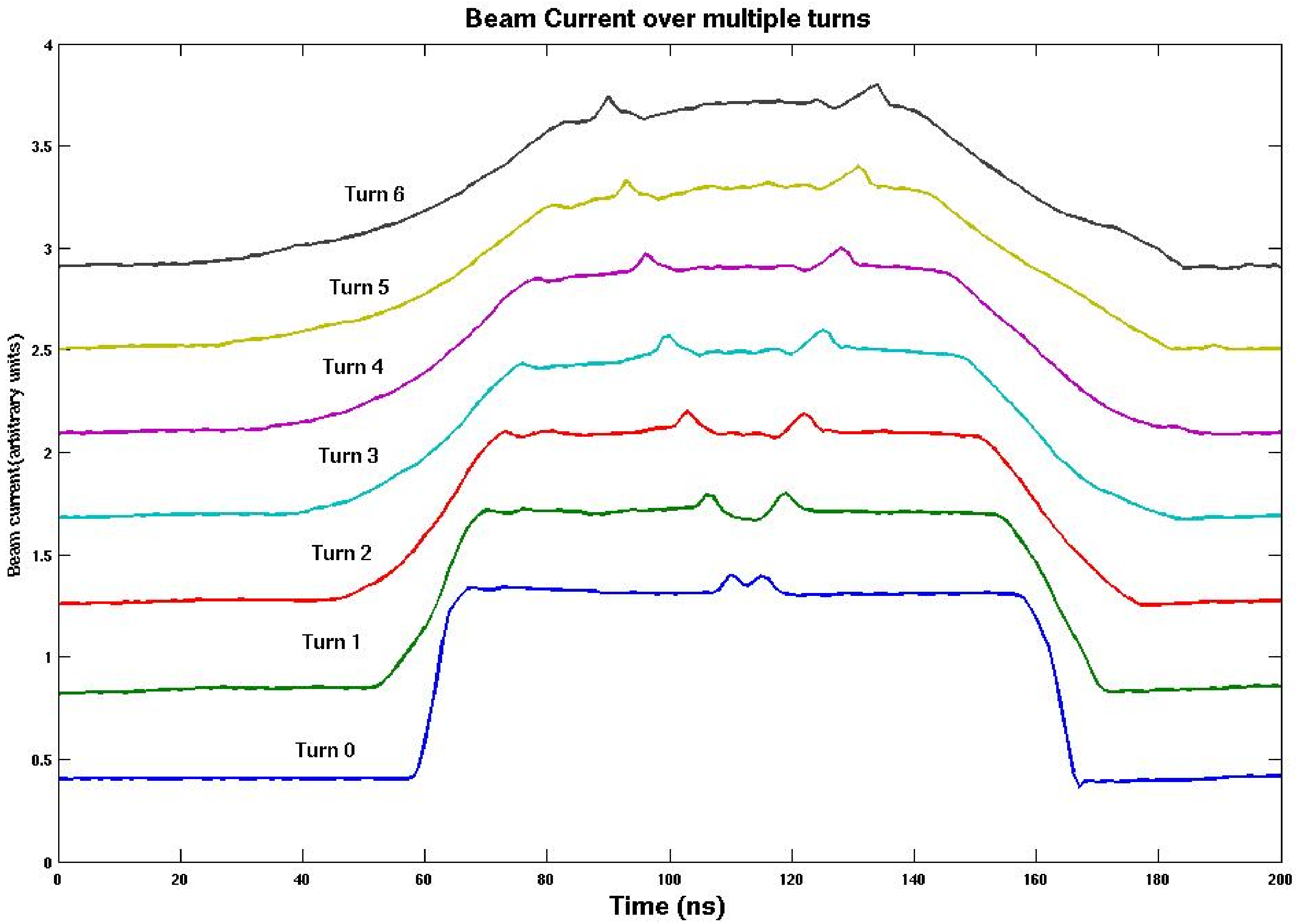
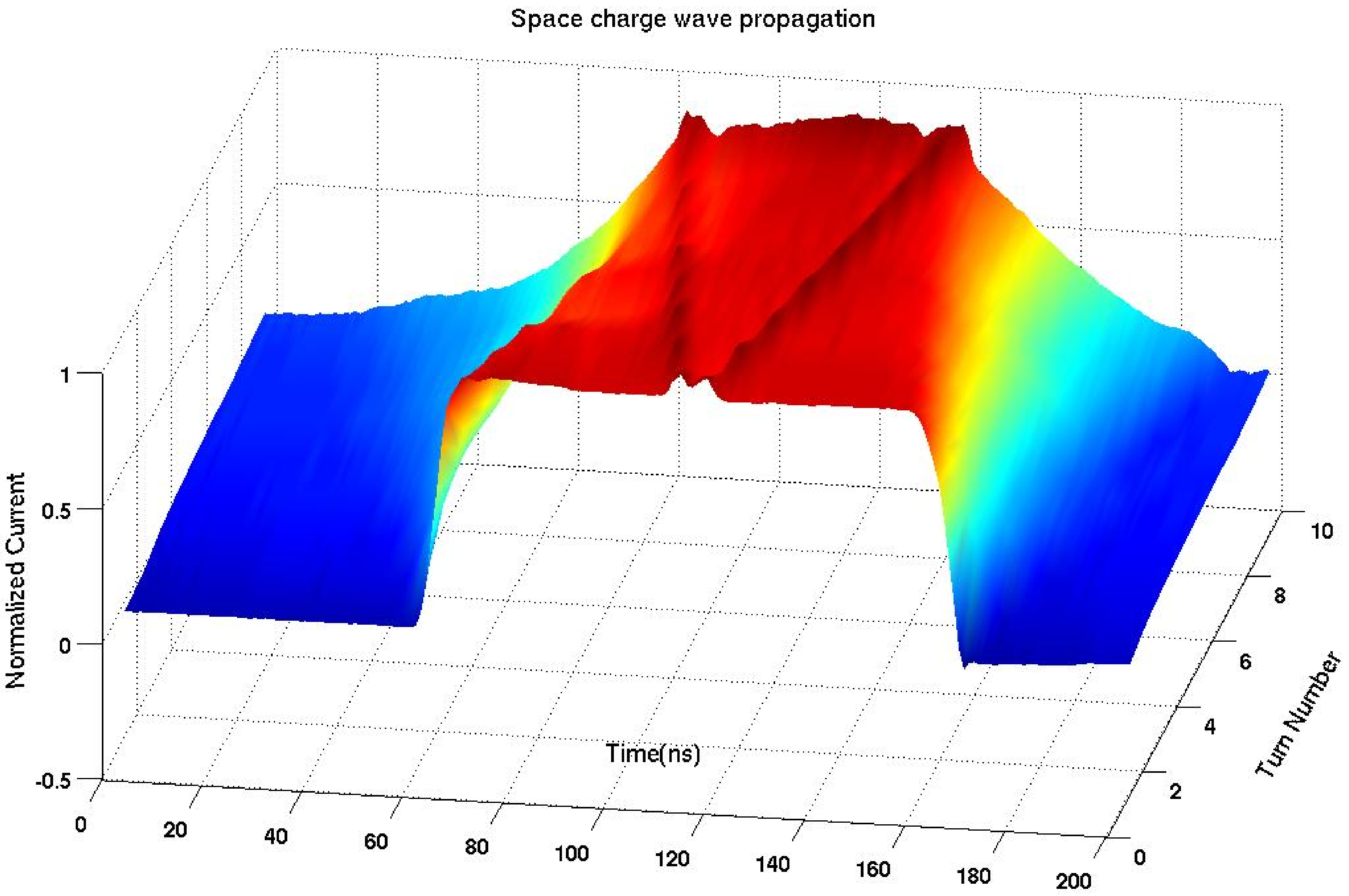
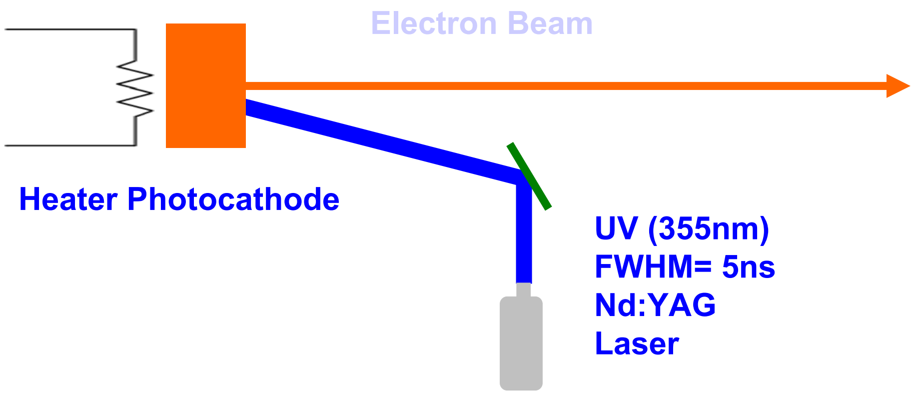
Multiturn observation of waves in UMER



Multiturn observation of waves in UMER



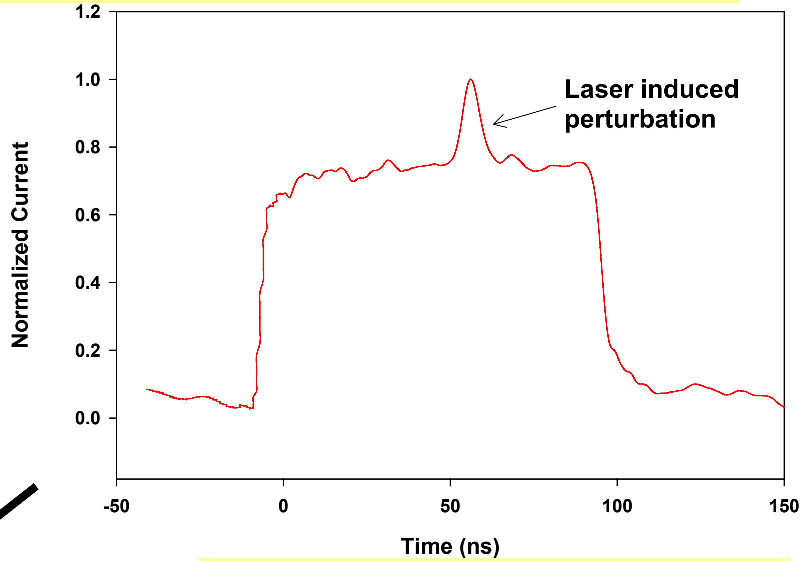
Space Charge Waves & Instabilities



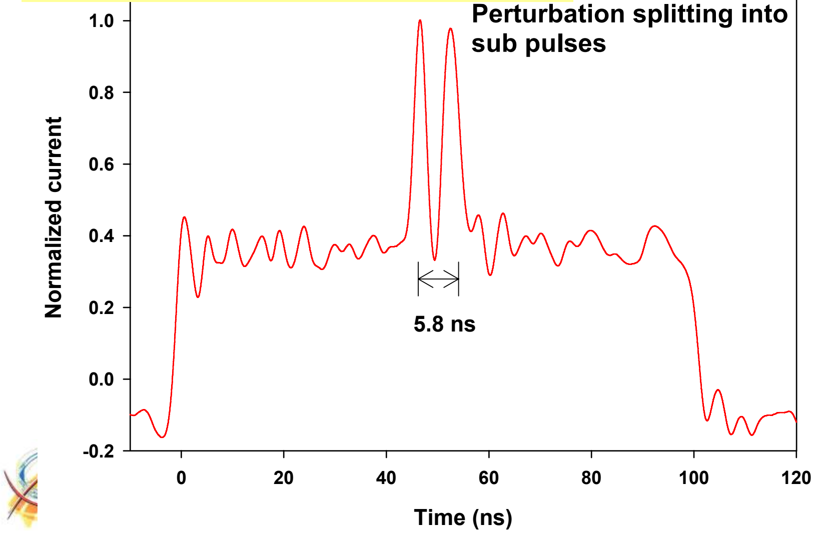
Electron Beam

Heater Photocathode

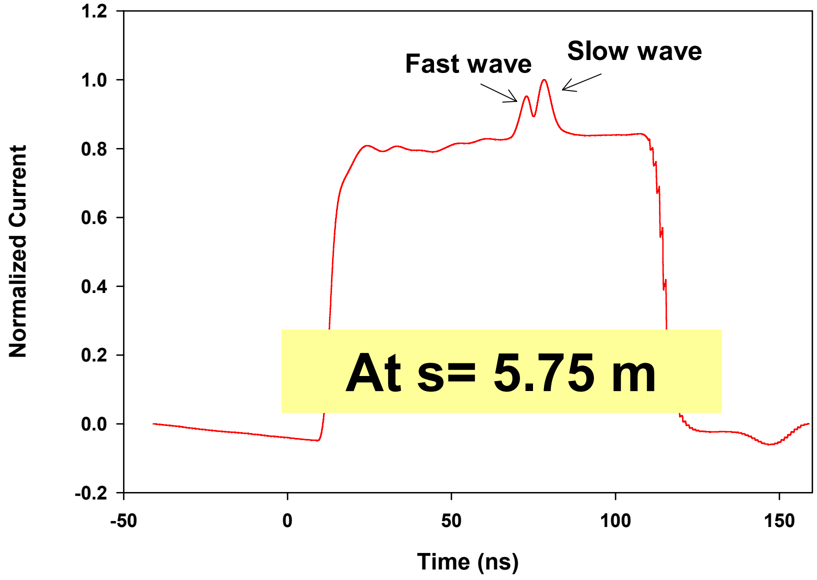
UV (355nm)
FWHM= 5ns
Nd:YAG
Laser



At large laser power: explosive splitting in gun



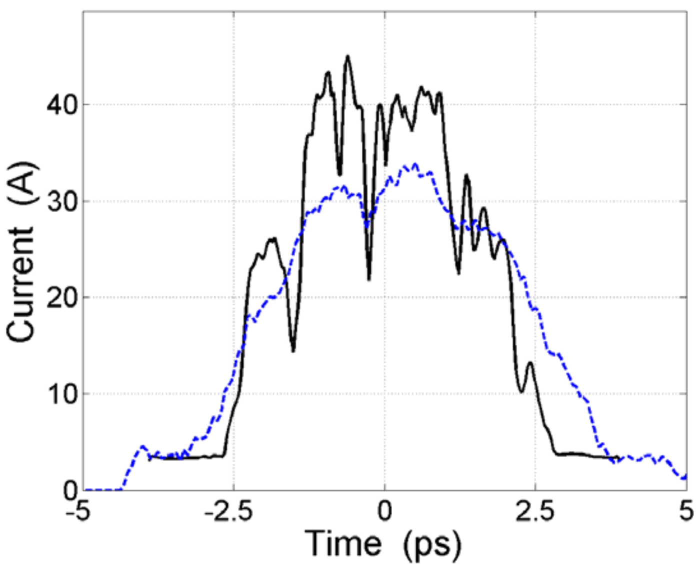
At low laser power: gentle splitting in transport

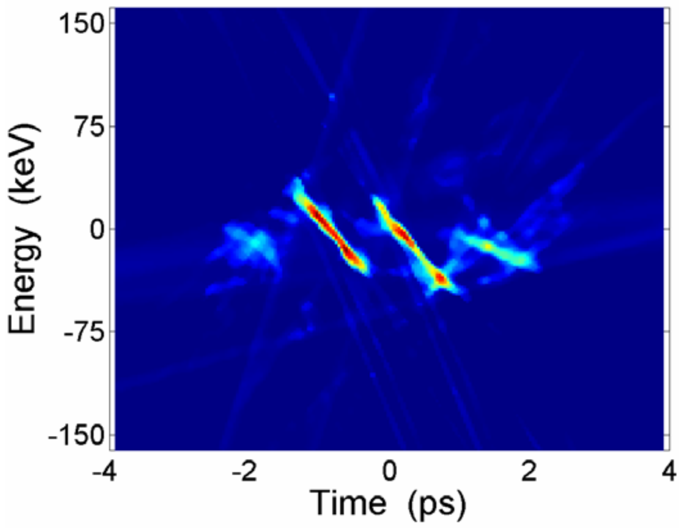


At s= 5.75 m

Space Charge Converts Density Modulation into Energy Modulations

Experiment at Brookhaven DUV FEL after perturbed beam is accelerated to 75 MeV





Q = 0.16 nC

Jonathan Neumann, Dissertation 2005

https://drum.umd.edu/dspace/handle/1903/2437

Is the inverse Humpty-Dumpty Effect possible ?

Humpty Dumpty sat on a wall.
Humpty Dumpty had a great fall.
All the king's horses and all the king's men
Couldn't put Humpty together again.

Illustration by John Tenniel From *Through the Looking-Glass*.