Lecture 6: Advanced RF technologies and lasers

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Advanced topics

- Multi-cell injectors
  - Standing wave
  - Hybrid
- Laser systems
  - Overview
  - Pulse shaping
- Selected beam diagnostics
  - Emittance measurements
  - Pulse length diagnostics

Multi-cell standing wave cavities

- Nearest neighbor coupling j^{th}-j+1th cell

$$\frac{d^2 I_j}{dt^2} + \omega_0^2 (1 + 2\kappa_c) I_j = \kappa_c \omega_0^2 \left[I_{j+1} + I_{j-1} \right]$$

- Assume modes like discrete-mass loaded string $I_j = a_j \exp(i\psi_j) \exp(i\omega_j t)$
- We have recursion relation

$$-a_{j-1}\kappa_c\omega_0^2 + \left[\omega_0^2(1 + 2\kappa_c) - \omega^2\right] a_j - a_{j+1}\kappa_c\omega_0^2 = 0$$

- Assuming $\psi_j = jb$ we have

$$-e^{-ib} + \left[\omega_0^2(1 + 2\kappa_c) - \omega^2\right] - e^{ib} = 0 \quad \text{or}$$

$$\omega^2 = \omega_0^2 + 2\kappa_c\omega_0^2\left[1 - \cos(b)\right] = \omega_0^2\left[1 + 4\kappa_c \sin^2\left(\frac{b}{2}\right)\right]$$

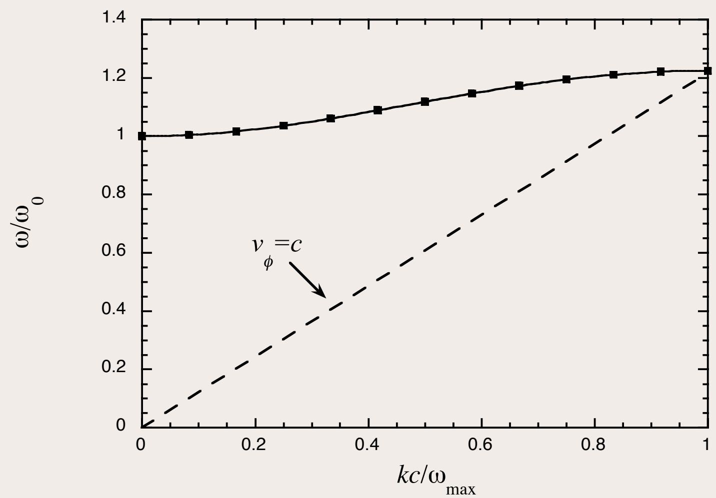
Modes in the pass-band

- Boundary conditions at end cells: $a_1 = 1 \quad a_{N_c} = \pm 1$
- Satisfied if

$$N_c b = n\pi \quad n = 0,1,2\ldots N_c - 1$$

- Substitute $b_n = \dfrac{n\pi}{N_c - 1}$, the phase shift per cell
- Dispersion relation

$$\omega_n = \omega_0\sqrt{1 + 4\kappa_c \sin^2\left(\frac{k_n d}{2}\right)} = \omega_0\sqrt{1 + 4\kappa_c \sin^2\left(\frac{n\pi}{2(N_c - 1)}\right)}$$



Brillouin diagram

Standing wave structures

- Standing wave, modes must be exactly excited.
- For many cells, mode separation can be very small, especially π-to-nearest neighbor
- Separation for large N_c requires large coupling

$$\kappa_c \left(\frac{\pi}{2N_c} \right)^2 >> \frac{1}{Q_L}$$

- Strict limit on N_c and/or creativity in coupling

Traveling wave structures

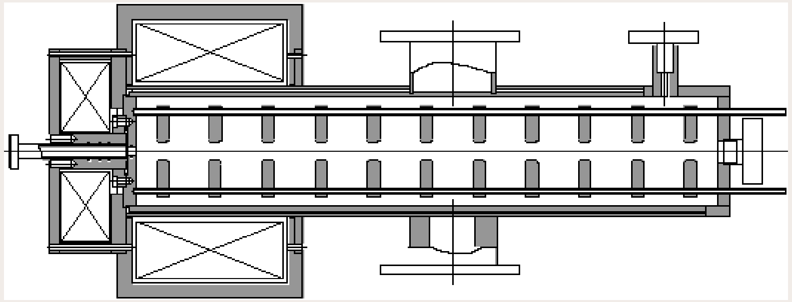
- Act like waveguides with

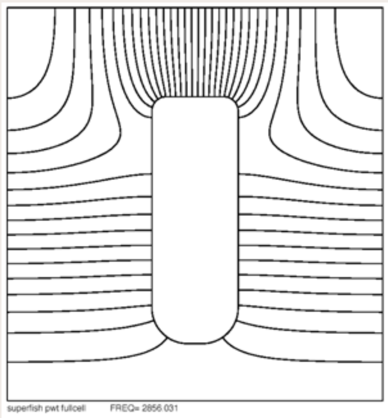
$$v_{\phi,n} = \frac{\omega_n}{k_n} = \frac{\omega_0 \sqrt{1 + 4\kappa_c \sin^2\left(\frac{k_n d}{2}\right)}}{k_n} \qquad v_{g,n} = \left.\frac{d\omega}{dk}\right|_{k=k_n} = 2\kappa_c \omega_0 d \frac{\sin\left(\frac{k_n d}{2}\right)\cos\left(\frac{k_n d}{2}\right)}{\sqrt{1 + 4\kappa_c \sin^2\left(\frac{k_n d}{2}\right)}}$$

- Power flows from input coupler to output, which is an impedance matched load
- Structure looks "infinite", entire pass-band is allowed.
- Much easier tuning, very long structures
  - SLAC 3 m TW section, 86 cells
- End cells look like SW to the beam, are "matching networks" to the RF.

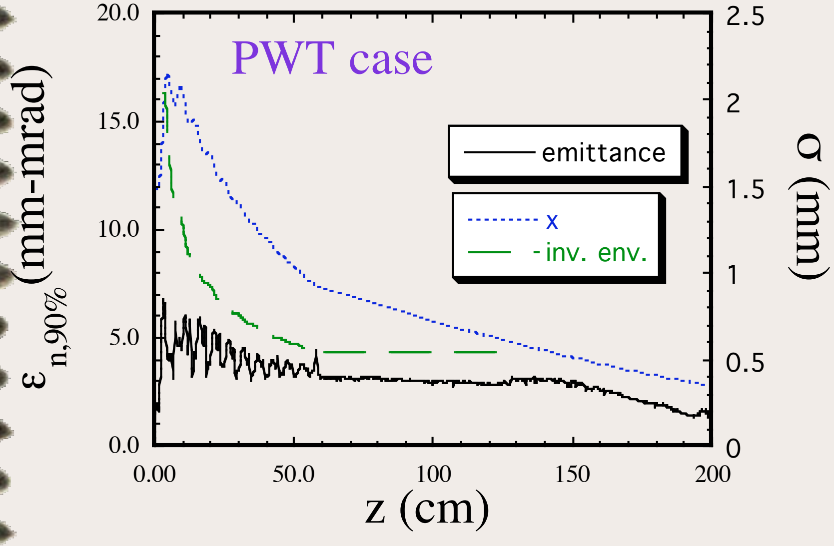
The PWT SW photoinjector

- Very large electric coupling obtained
- Passband is 900 MHz out of 2856 MHz!
- Large structure, stored energy. High *Q*.
- Elaborate solenoid
- Installed at UCLA PEGASUS lab.





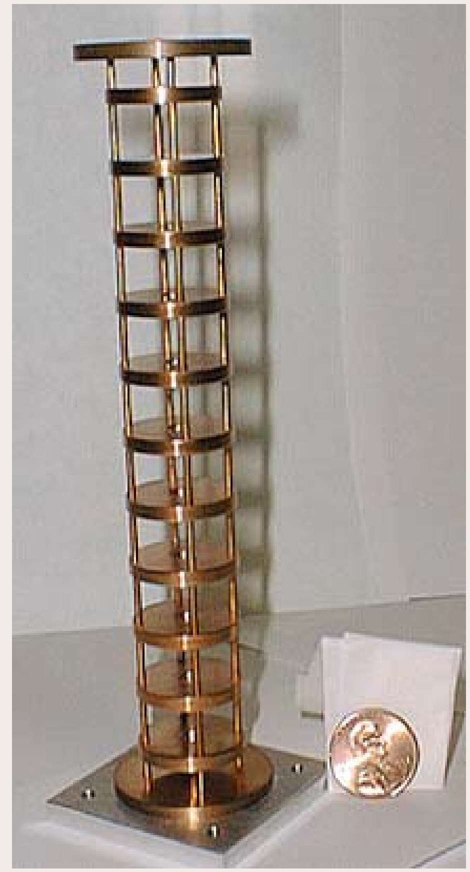
PWT has good performance, low accelerating field



- Run at 60 MV/m peak on-axis field
- Beam hard to match to invariant envelope
- Solenoid field much smaller
  - Low energy
  - Do not fight RF defocusing kick
- Performance not as good at 1 nC as "split" photoinjector
  - But scalable design!

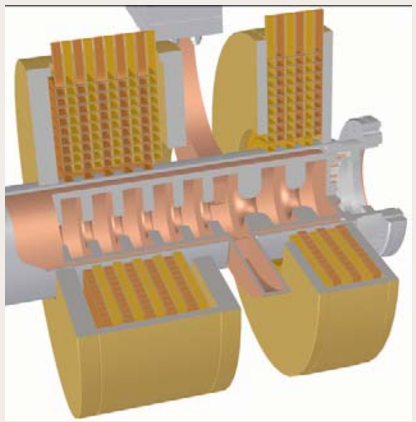
X-band photoinjector

- PWT injector scaled to 11.424 GHz
- Design indicates higher brightness than S-band Ferrario case
- Not yet produced
  - Higher RF power needed
  - Cooling is difficult
  - Solenoid is difficult
  - How to handle reflections of RF wave?
- More promising: hybrid structure

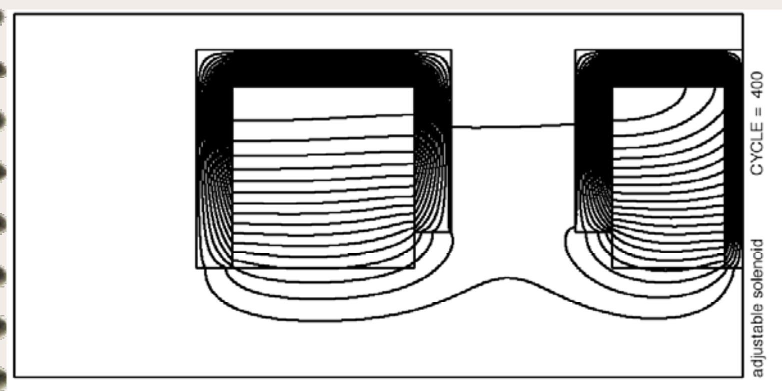


UCLA X-band PWT cold test model (interior)

Hybrid photoinjector



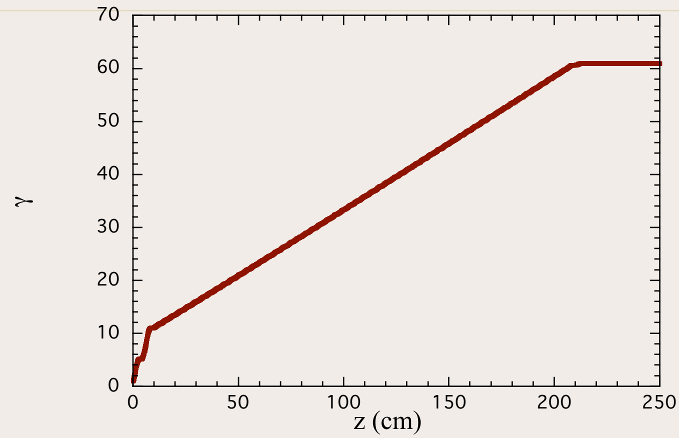
Hybrid structure

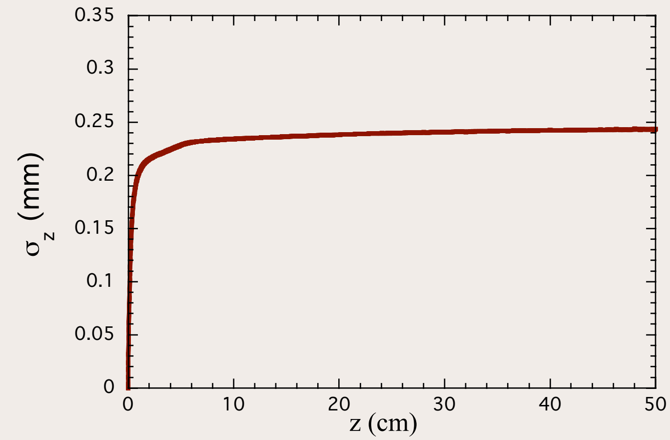


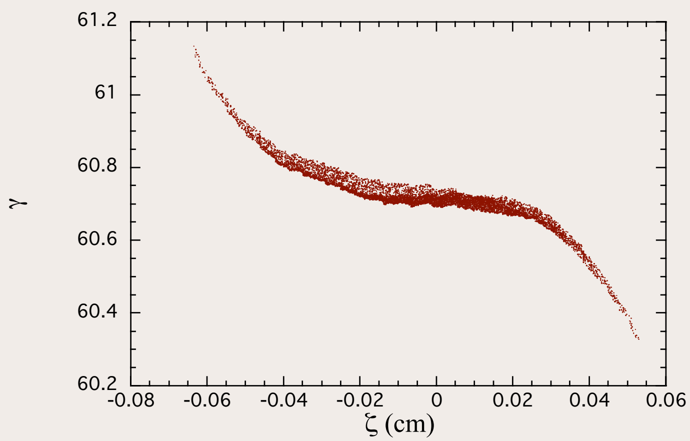
Emittance compensation solendoid for hybrid

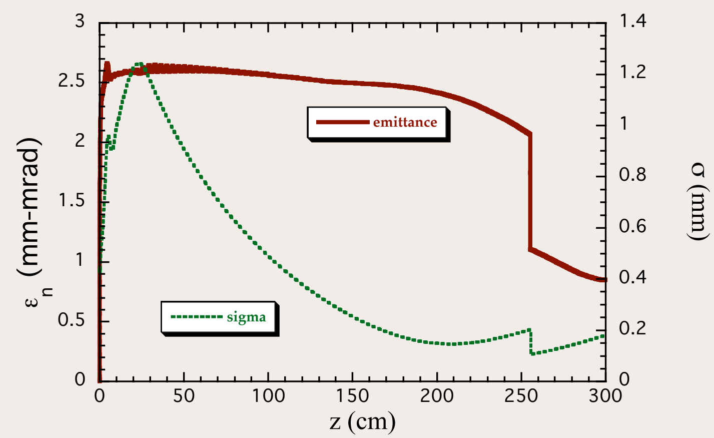
- Couple to third cell
- Feed RF power on-axis to
  - Vestigial "gun" section
  - TW section
- Most power goes to TW
  - 2 MW gun, 20 MW linac
  - Strongly suppress reflection
- Use long TW to obtain high energy, low gradient
  - Efficient use of RF power
- Under development at UCLA and INFN

High energy, low emittance, sub-ps, 1nC beam obtained in long structure









Collimation of halo (long, near equilibrium propagation)

One last idea…

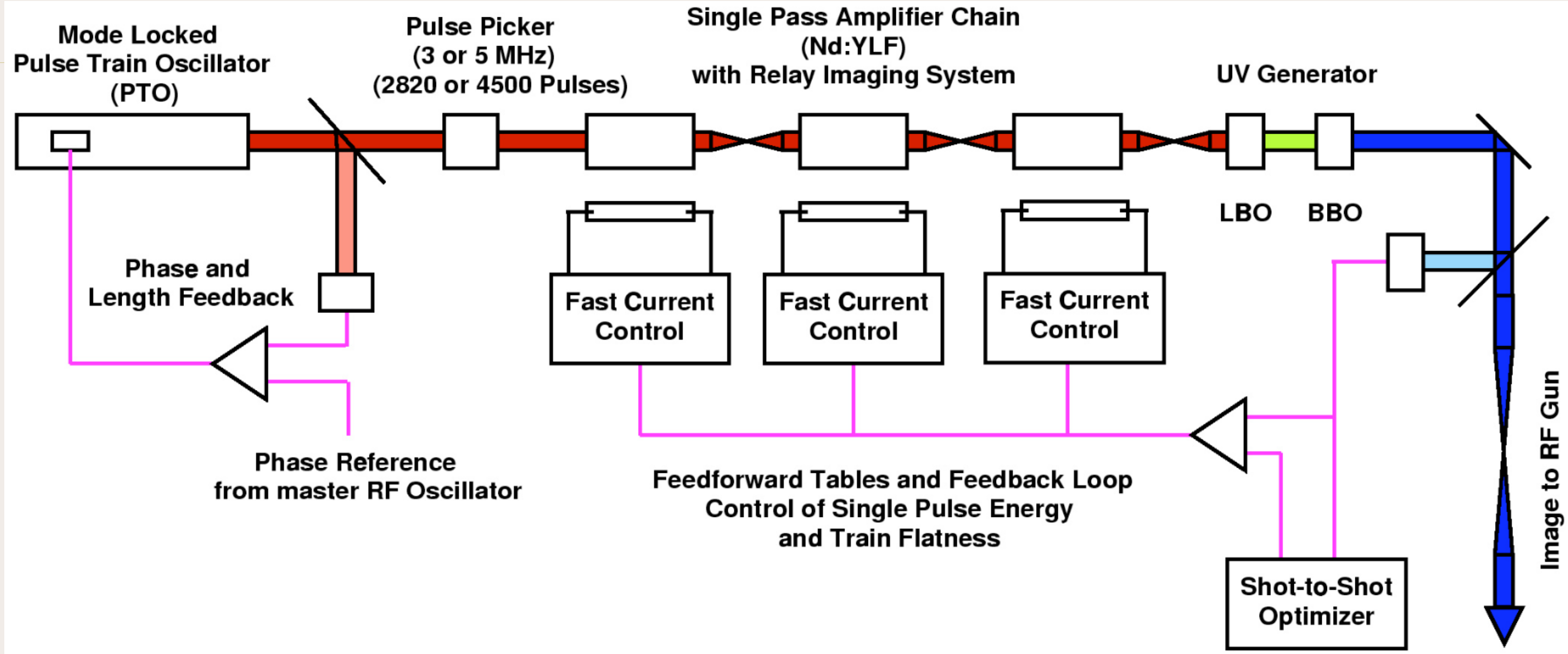
- Superconducting RF gun
- For CW applications (ERLs, etc.)
- Ferrario, tomorrow

Laser systems for photoinjectors

- Deliver high photon number in < ps
- Pulse shaping in t and ρ. Uniform "beer can" distribution
- Excellent pulse-to-pulse stability
  - Energy
  - Timing
  - Pointing jitter

The first beer can!

Overview of "typical" system

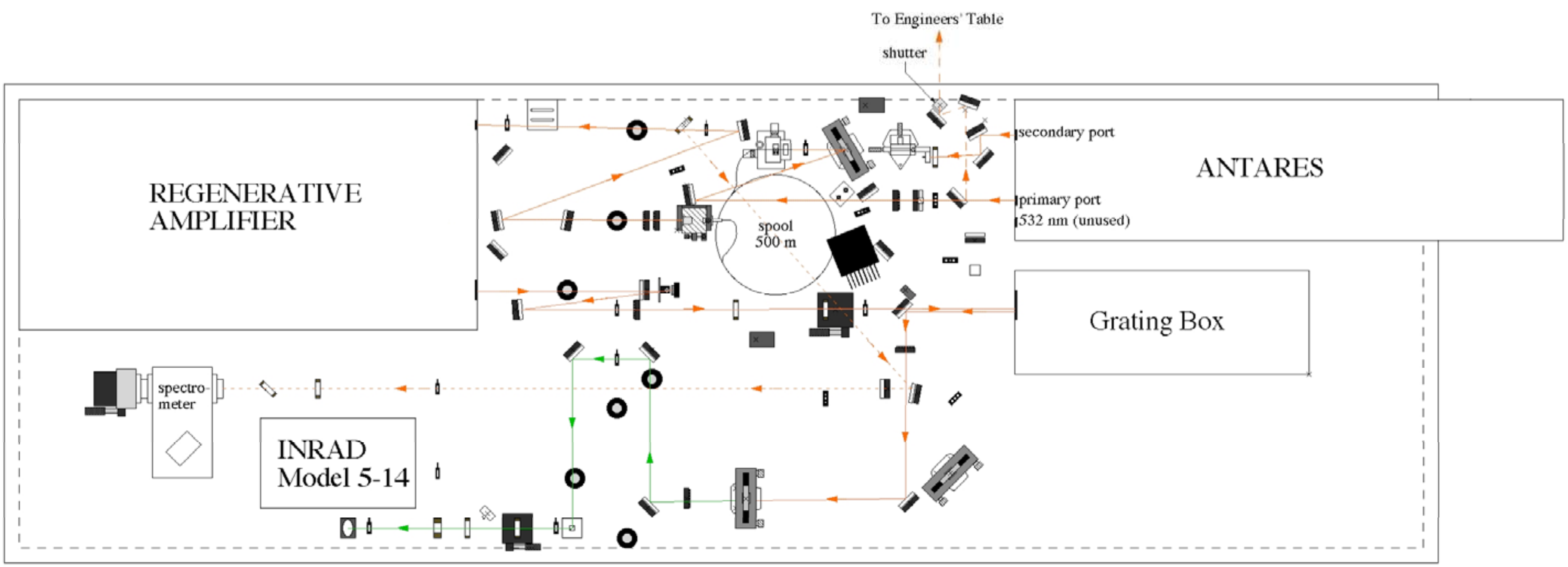


- SPARC injector system proposal
- Note use of relay imaging (obtain flat-top in radial profile)

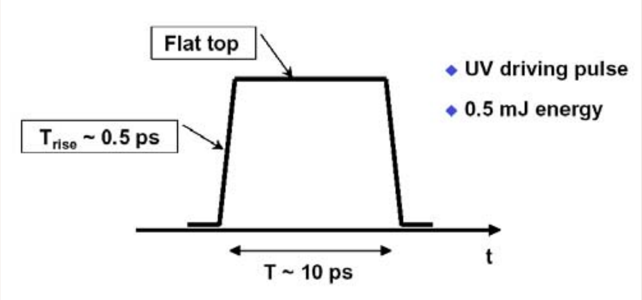
A more detailed look

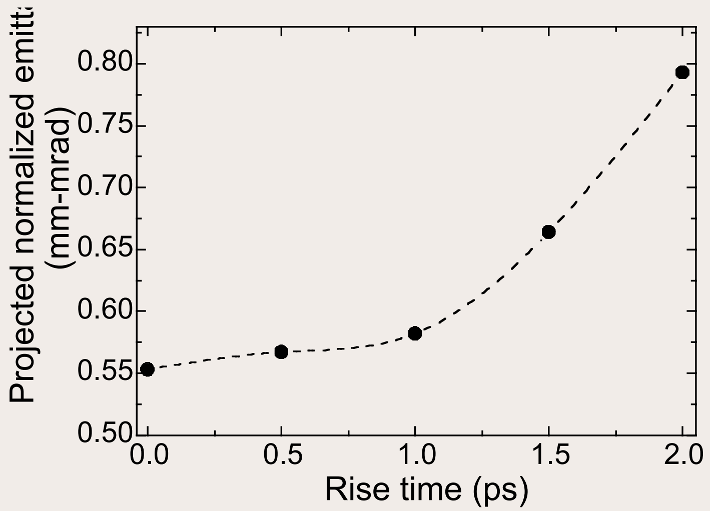
- Neptune photoinjector drive laser
- First generation chirped pulse amplification laser
- Based on fiber self-phase modulation/group velocity dispersion
- Must have enough bandwidth in system to make short pulse (structure)

$$\Delta\omega\Delta t \approx 1$$



Tailoring the laser pulse: rise time effects on beam emittance





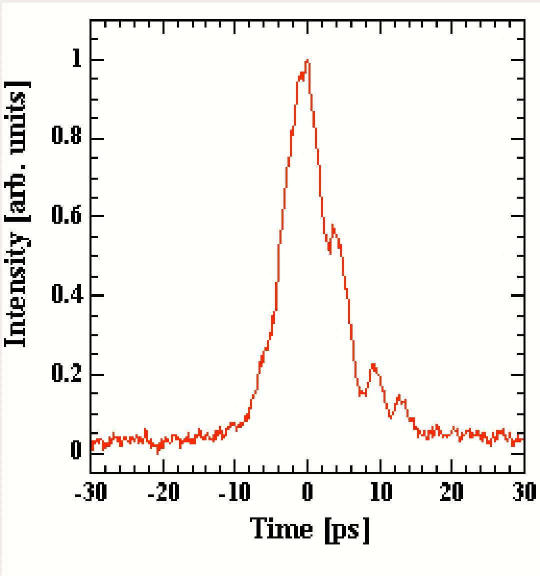
SPARC design study of pulse rise time

Achieving Uniform Bunch Distributions using Flat-Top Laser Pulses (Sumitomo)

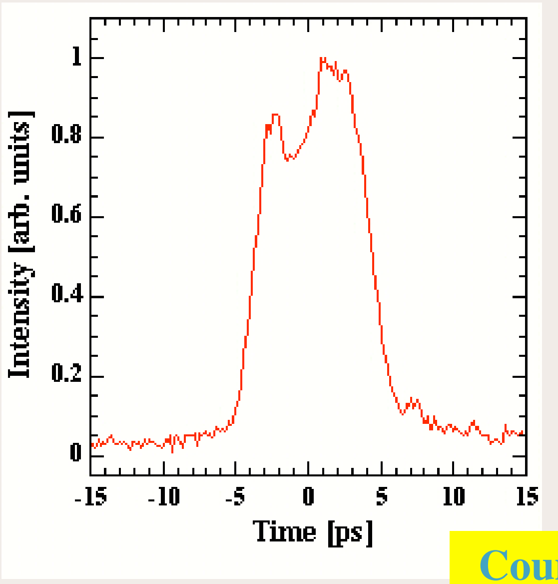
Temporal distributions of shaped UV laser pulses

by streak camera

Gaussian pulse shape



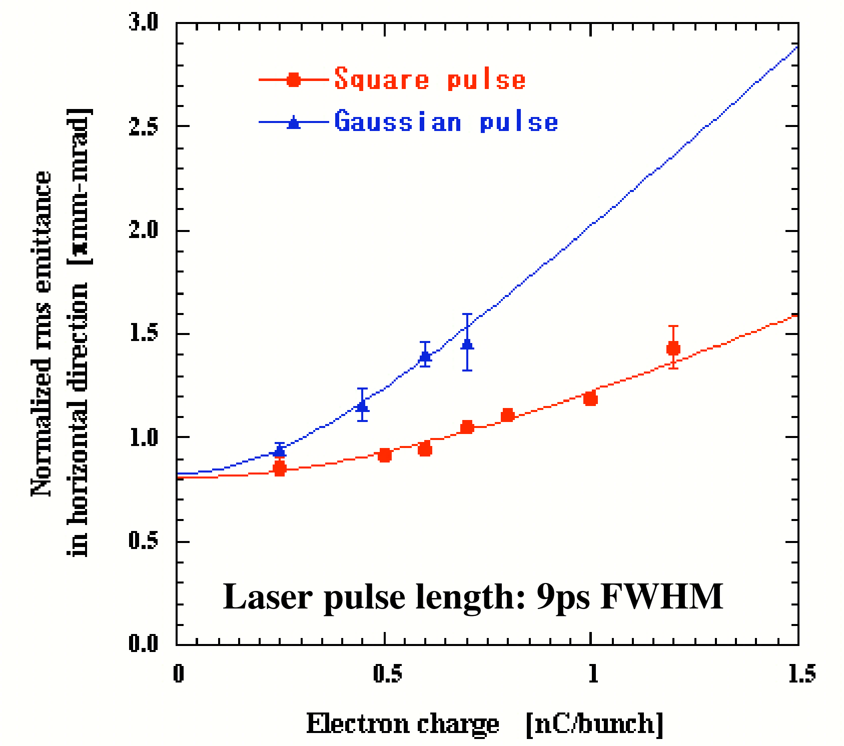
Square pulse shape



Courtesy of F. Sakai

- **The flatness of square-shaped laser pulse:**
  5~25% @ 4~14 ps FWHM
- **The fluctuation of shaped pulse length:**
  7% (pulse-to-pulse)@both shapes

Emittance measurements for gaussian and "square" laser pulse shapes



Courtesy of F. Sakai

Summary of SPARC Drive Laser Parameter Set With Tolerances

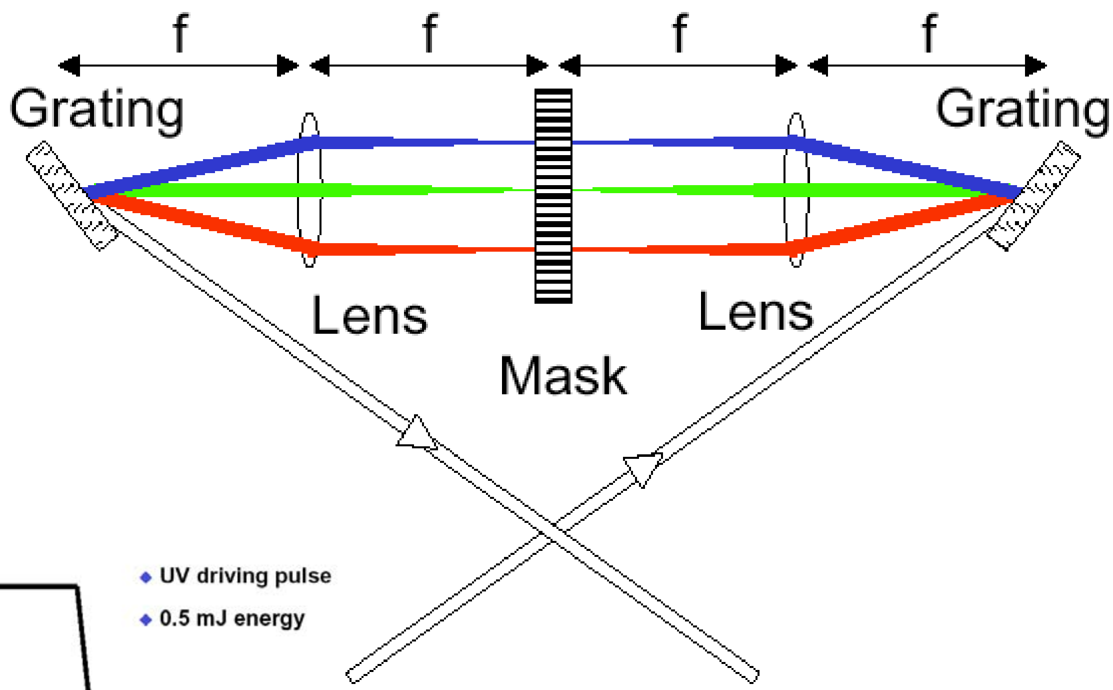
Parameter	Requirement
Operating Wavelength	260 nm
Pulse energy on cathode	500μJ (η=10^{-5})
Energy jitter (in UV)	5 % rms
Temporal pulse shape	Uniform (20% ptp)
Transverse pulse shape	Uniform (20% ptp)
Pulse rise time (10-90%)	< 1 ps
Pulse length	2-10 ps FWHM
Repetition rate	10-20 Hz
Laser-RF jitter	< 1ps rms
Spot diameter on cathode	Circular 1 mm radius

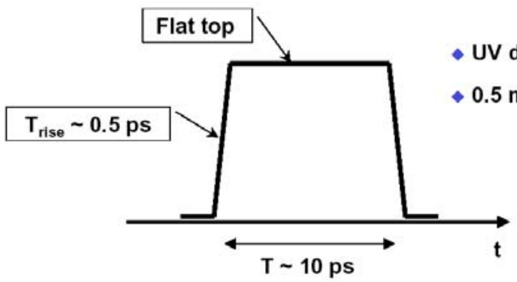
Solution paths for laser system

- Bandwidth from Ti:Sapphire, or?
- All diode-pumped systems for stability
- Lock-to-rf clock of oscillator mode-locker
- Tight control over environment
  - Temperature
  - Air currents
  - Vibrations
- Some creativity over pulse shaping
  - Do better than Sumitomo!

Spectral mask in Fourier (frequency) plane - mid-compressor

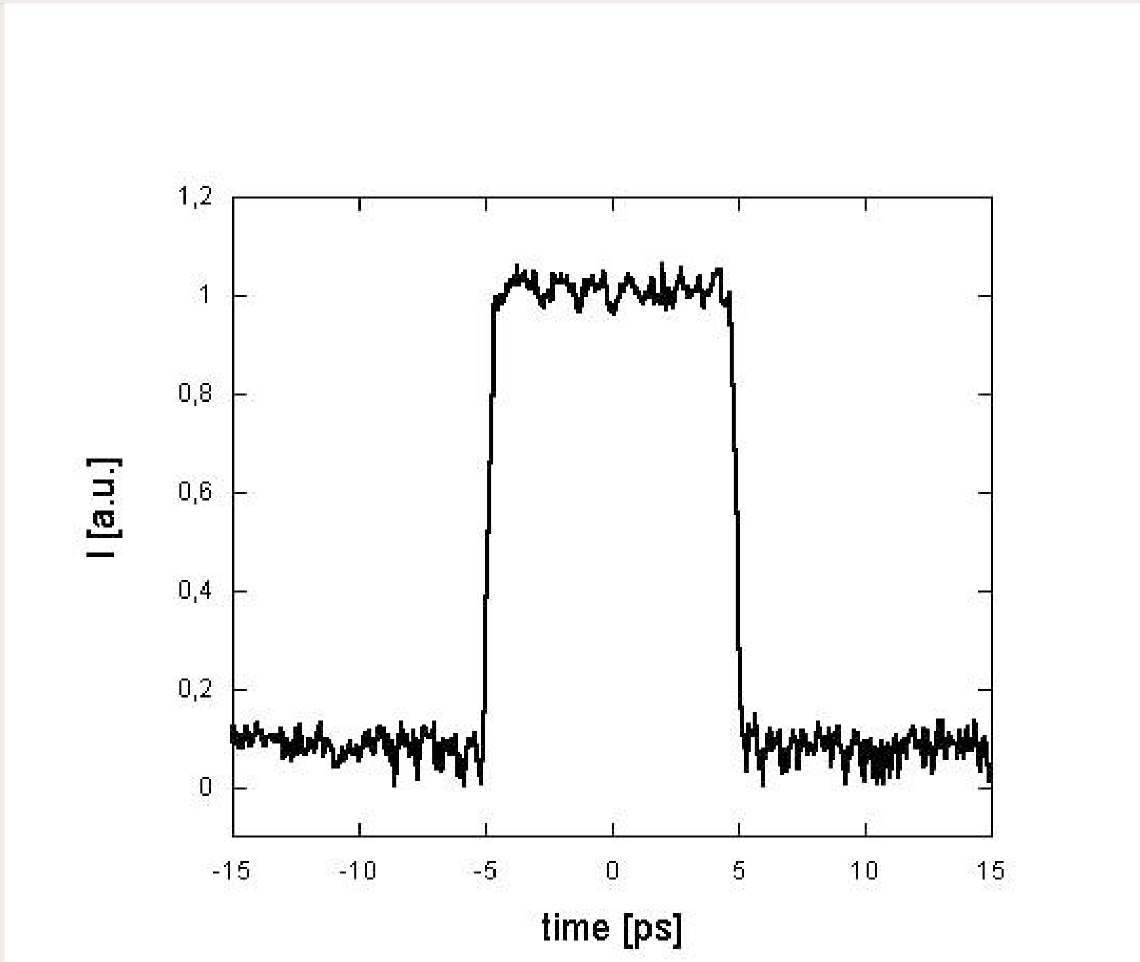
Mapping of spectral domain into spatial domain





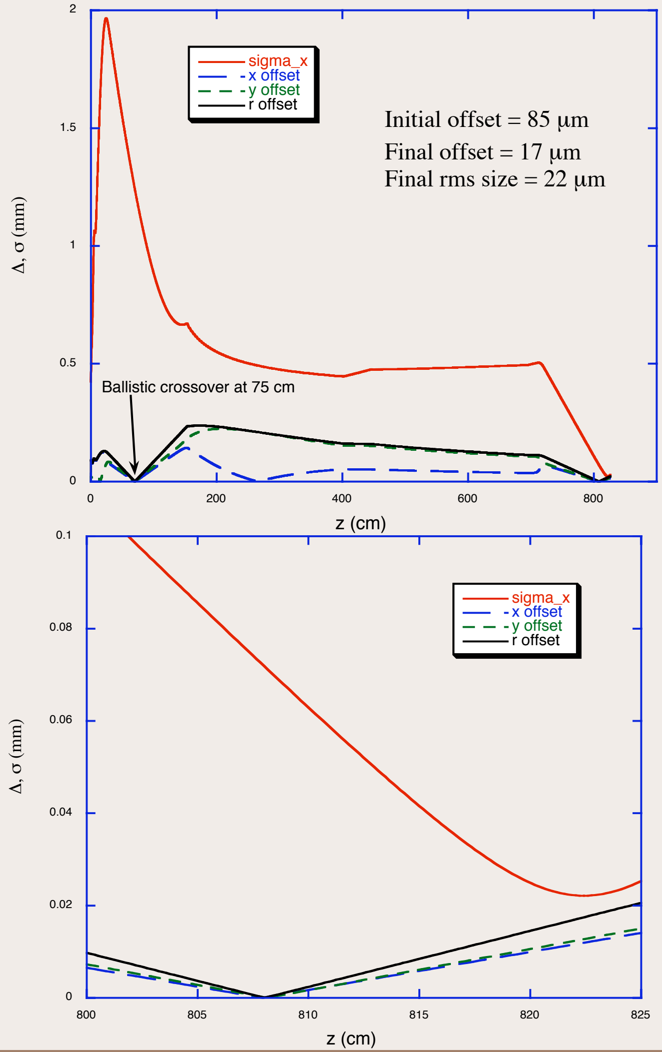
- UV driving pulse
- 0.5 mJ energy

Simulations of SPARC LCM system



Other options: Acousto-optic modulator

Laser pointing jitter



- Focusing is set up for space-charge dominate beam (compensation)
- Offset behaves as single particle
- Offset can be bigger than rms size at focus!
- Careful relay imaging and vibration control

LLNL ICS photoinjector
Close-up on focus region

Problems for Lecture 6

9. Assume that you have a 12-cell standing wave RF structure, and that the coupling κ is 0.05. What is the tolerable *Q* of the π-mode so that it does not overlap with the nearest mode (2 *Q*-widths separation). Assume you originally have 4 *Q*-widths separation, and you scale the entire structure in frequency upwards (e.g. S- to X-band), how much can you raise the frequency while maintaining acceptable overlap?

10. What is the relative bandwidth of a 30 fs (state of the art) drive laser, at 266 nm wavelength? What is the spread in photon energy associated with this laser. What do you think the effects on the quantum efficiency, and the "thermal" emittance are of such a spread?