Optimum beam creation in photoinjectors using space-charge expansion II: experiment

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Basic Experimental Demands

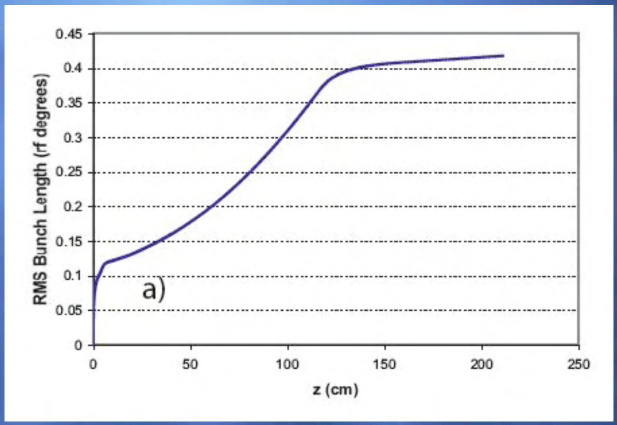
- Luiten-Serafini scheme test
- (My) defining characteristics
  - Ultra-short laser (100's fs, arbitrary pulse shape)
  - Radial shaping $I(r) = I_0\left(1-(r/a)^2\right)^{1/2}$
  - Optimum emittance compensation (LCLS scenario)
- We have examined at several appropriate photoinjectors:
  - LLNL PLEIADES:
  - SLAC NCLTA ("ORION", "E163"
  - SPARC (Frascati)

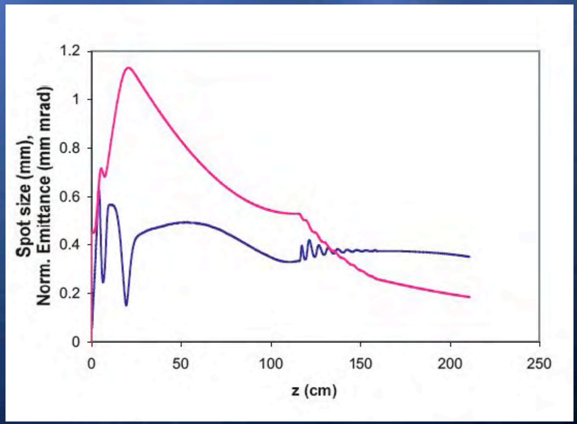
Experimental possibilities

- LLNL PLEIADES:
  - Proposed w/S. Anderson for LDRD
  - non-optimized scenario
  - difficult funding of machine at present…
- SLAC NCLTA ("ORION", "E163")
  - Driver for TW undulator FEL
  - Good for ORION program, including laser acceleration
  - Winter 2005?
- SPARC (Frascati)
  - Optimized environment
  - Begining Fall 2005
  - Discuss mainly from this perspective

PLEIADES Proposal

- S. Anderson study
- 60 fs FWHM laser assumed, prompt emission of 100 pC
- Perfect Luiten profile
  - Use deformable mirror
- Short gun/linac drift
- 100 A beam
- Excellent emittance: 0.4 mm-mrad
- PLEIADES on “hiatus”

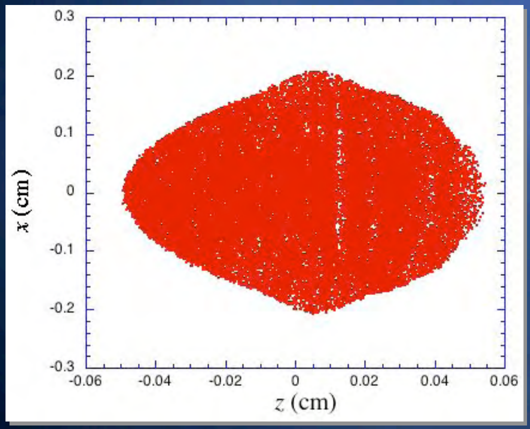




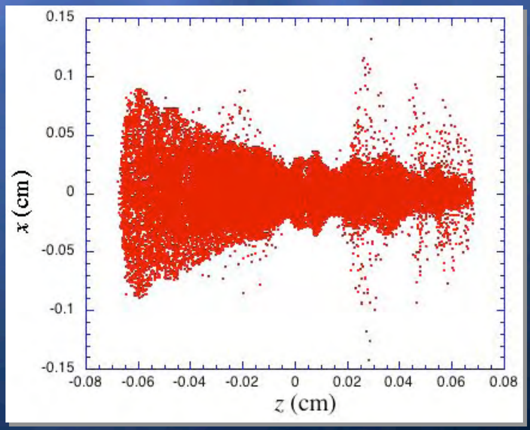
PARMELA sims (courtesy S. Anderson)

Ellipsoidal beam at SPARC

- Launch 0.33 nC, 120 MV/m peak gun field, 2.7 kG solenoid
- Laser assumed 80 fs in initial study (Gaussian, to 3σ)
- Some longitudinal asymmetry due to image charge
- Small artifact from non-ideal radial profile (cut-Gaussian, 1.8σ)
- At low energy (only) ellipsoidal beam shape is visible

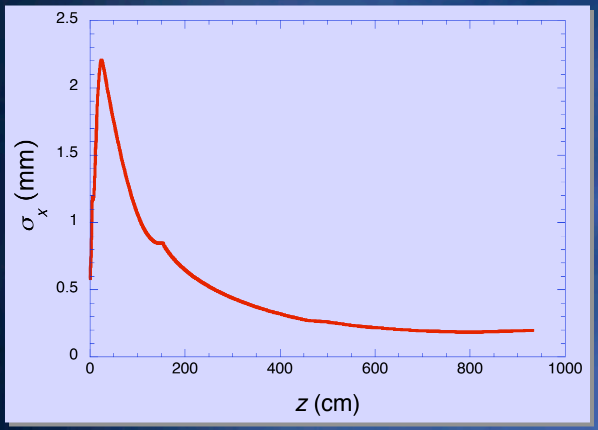


Beam distribution showing ellipsoidal boundary (12.5 MeV)

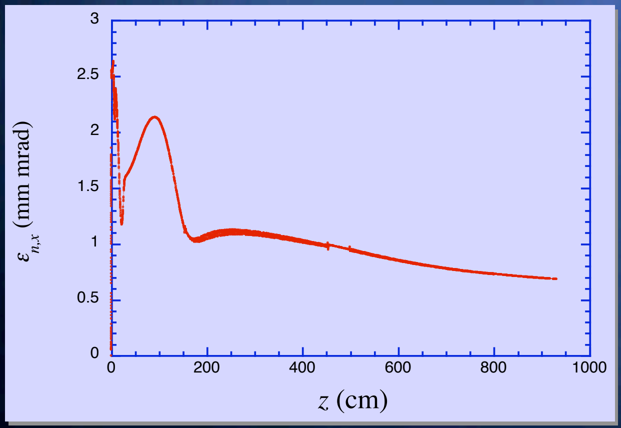


Beam distribution at high energy shows Boundary collapse (84.5 MeV)

SPARC emittance compensation



Beam size evolution

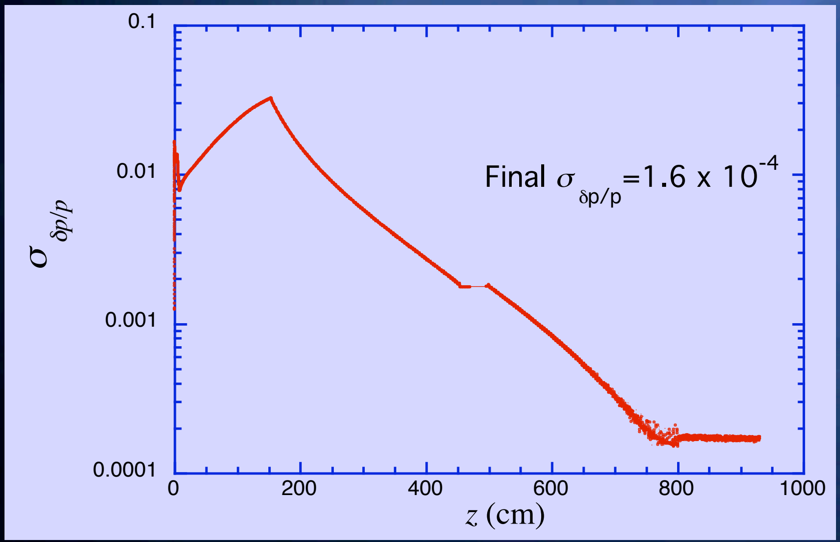


RMS emittance evolution

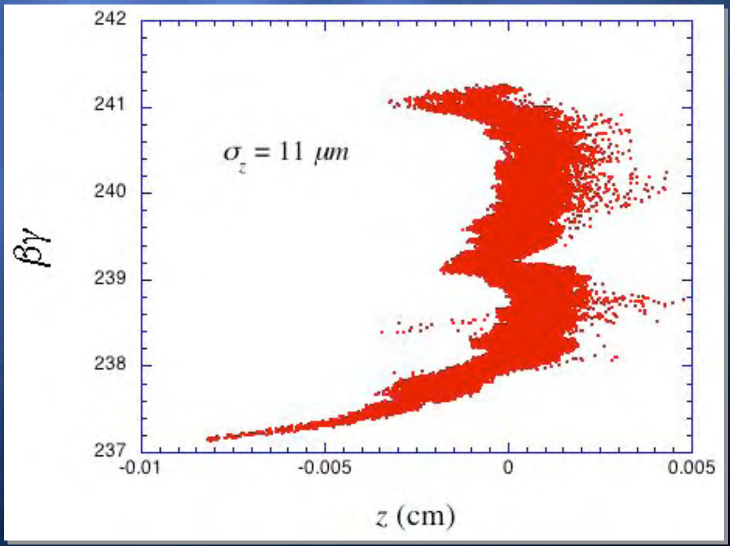
- Final emittance <0.7 mm mrad
- Measure emittance at low energy and high
  - SPARC phase 0 (gun only)
  - Full SPARC energy

Longitudinal phase space advantages

- Initial fast — but not large — longitudinal emittance growth due to rearrangement/expansion
- Shortest pulse possible given E-field
- Extremely small final energy spread
  - Shorter beam
  - Approx. linear space charge (linear chirp contribution)
- Excellent compression! Use as diagnostic of SC forces



Energy spread evolution



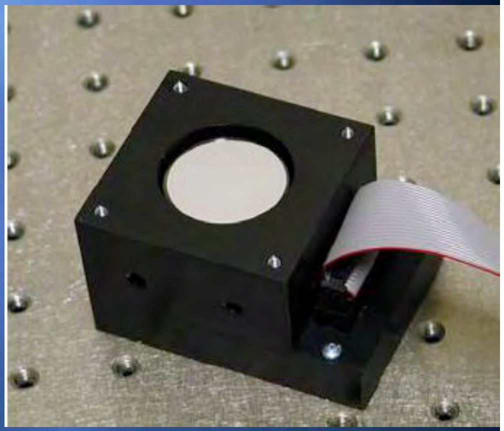
Longitudinal phase space after compression

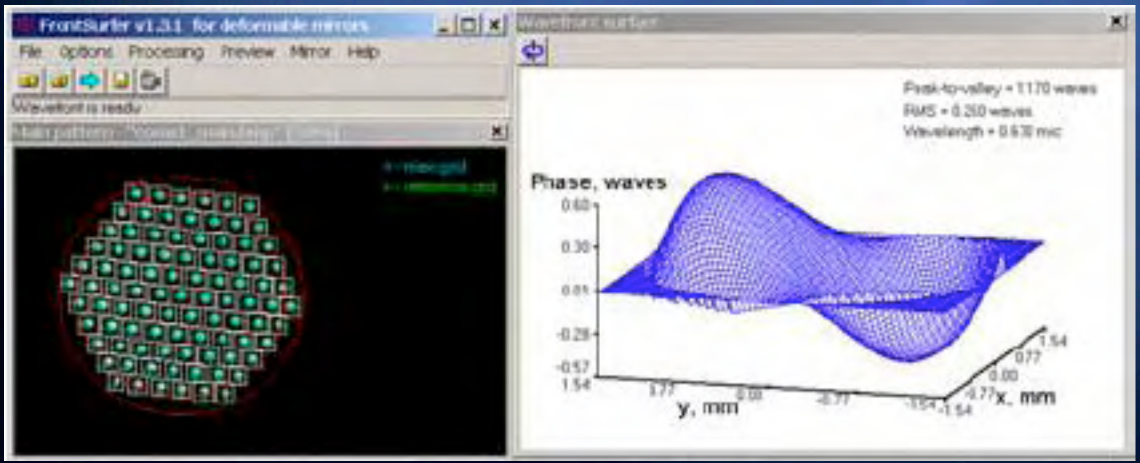
Experimental details and status

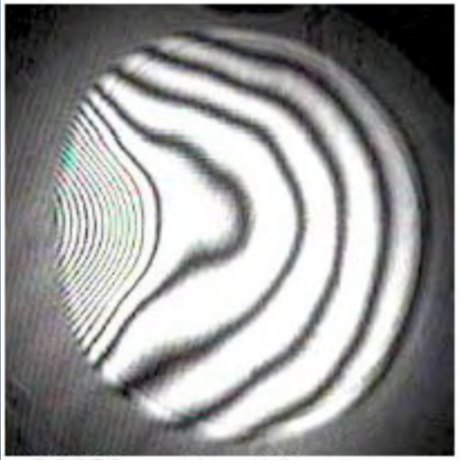
- Experimental signatures
  - Good emittance*
  - High current/short pulse*
  - Ellipsoidal beam at low energy????
- Time-resolved measurements
  - Streak camera measurements
    - Under evaluation and/or construction
    - Cerenkov (aerogel)
    - OTR (at low energy…)
  - Other gating techniques…
  - RF deflector-based measurements

Experiment setup 1: laser shaping

- Pulse length (x-correlation) w/100 fs resol.
- Laser must be radially shaped
- "Cut-Gaussian" case easy
  - Collimation (soft aperture?)
  - Relay imaging
- Optimum shape hard (but better!)
  - Use deformable mirror to tailor



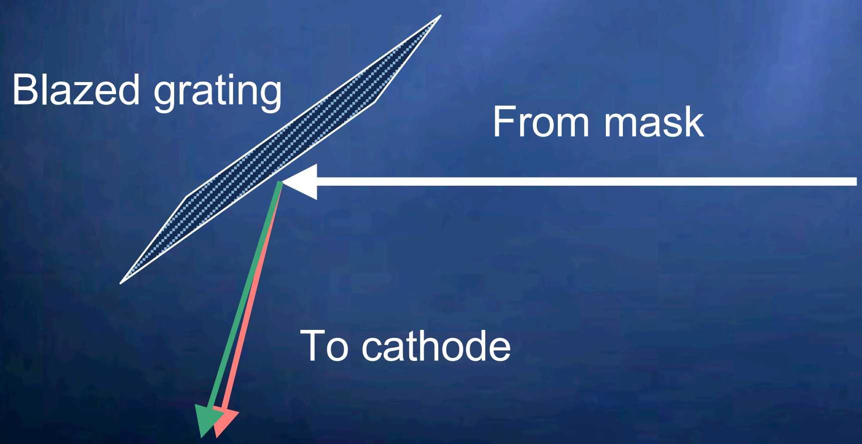




+300V on the side actuator

Experiment setup 2: Laser transport

- Relay imaging from mask
- Higher intensity laser induced breakdown
  - Assume <100 μJ (3E-4 J/cm^2) in 100 fs
  - Laser window? No problem (IR data)
- Measure/feedback at virtual cathode
- Pulse tilt complicated by bandwidth



Experiment setup 3: Laser on cathode

- Higher intensity laser effects
  - Breakdown on cathode? BNL "laser cleaning" indicates 0.12 J/cm^2 threshold
  - Scaling for equal field: 0.013 J/cm^2
  - Wild card: RF field…
- Laser heating of emitted electrons?
  - "Thermal emittance"

$$\varepsilon_n \cong a_l \sigma_x \cong \frac{\lambda_l}{2\pi m_e c^2}\sqrt{Z_0 P_l} \approx 0.04 \ \mathbf{mm\text{-}mrad}$$

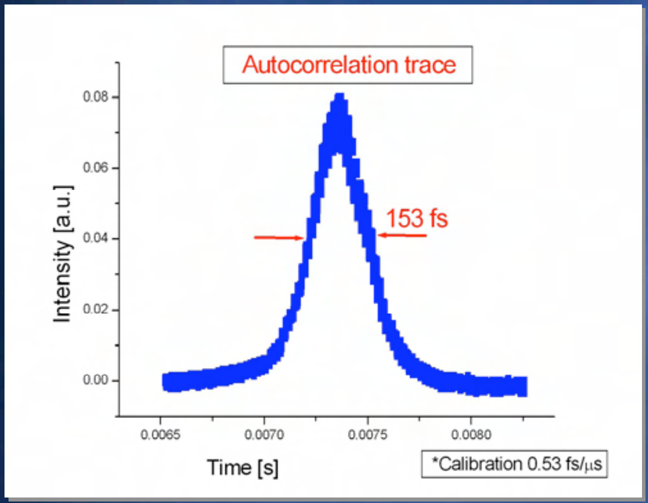
Cathode temporal response

- Metals
  - Mean deposition (photoelectron excitation) depth $l_d \cong k_p^{-1} \cong \left[4\pi r_e n_e\right]^{1/2} \approx 50\ \mathbf{nm}$
  - Velocity of photoelectron in material

$$v \cong c\left[2h\nu_l / m_e c^2\right]^{1/2} \approx 4.2 \cdot 10^{-3} c$$

  - Time response $\tau_e \cong l_d / v_e \approx 40\ \mathbf{fs}$
- Semiconductors
  - Longer time response…

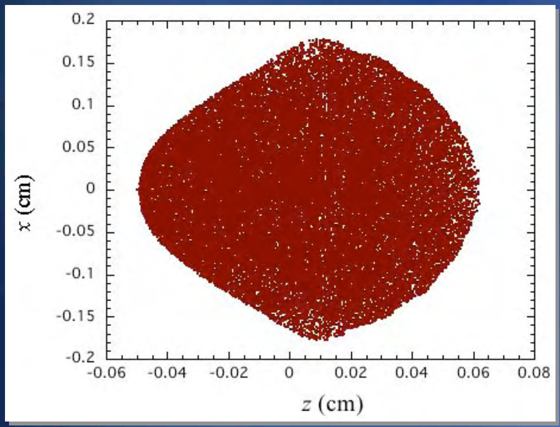
New problem: 3rd harmonic conversion pulse lengthening

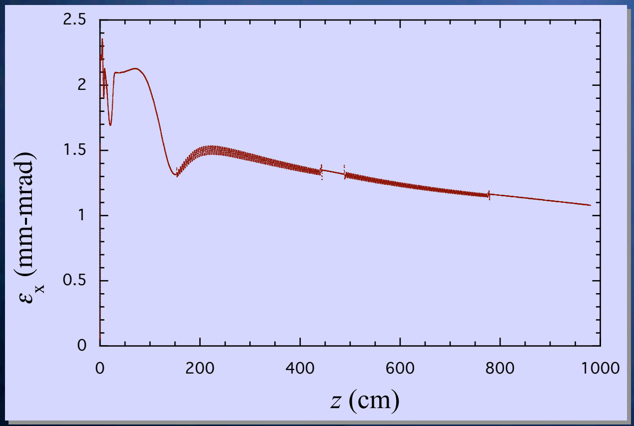


Autocorrlation of SPARC laser in IR (100 fs FWHM)

- Short pulse in IR
- Angles in 3rd harmonic generation produces long pulse in UV
- Measurements at SPARC laser: 310 fs FWHM

PARMELA simulation of longer laser scenario



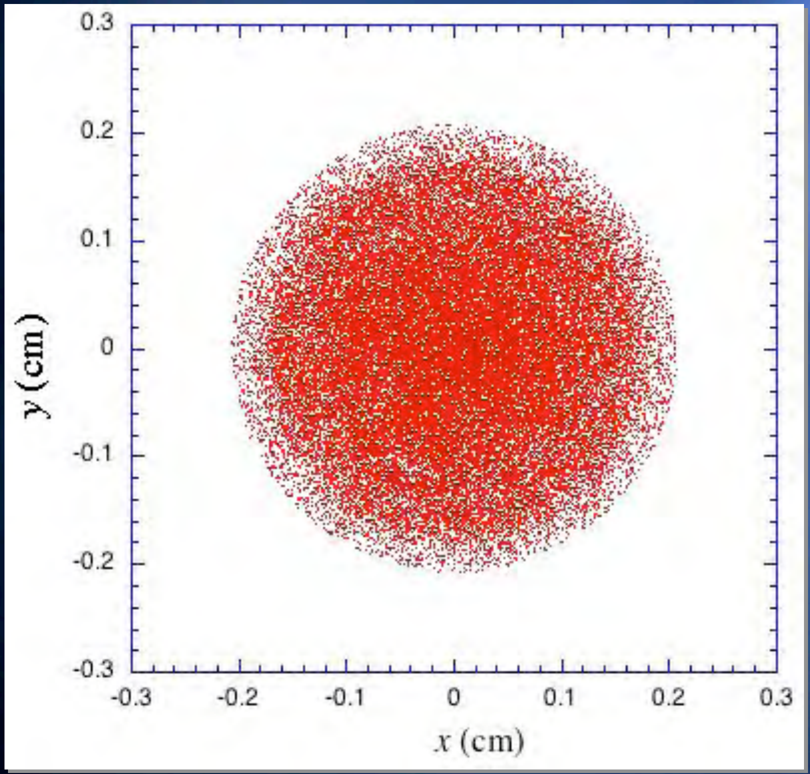


- Simulation with 310 fs (100 micron)
- Still short w.r.t. eventual pulse length
- Emittance more difficult
- More study needed

Measurements (non-exclusive)

- Beam distribution
  - Projections in *x* and *t*
  - Simultaneous imaging?
  - Best at low energy
- Emittance
  - Good performance (no other signatures?)
  - Measure at low energy slits
  - High energy measurement with phase space tomography
- Energy spectrum
  - Measured on crest
  - Compressibility! (longitudinal PS tomography?)

Diagnostics 1: Transverse pulse shape



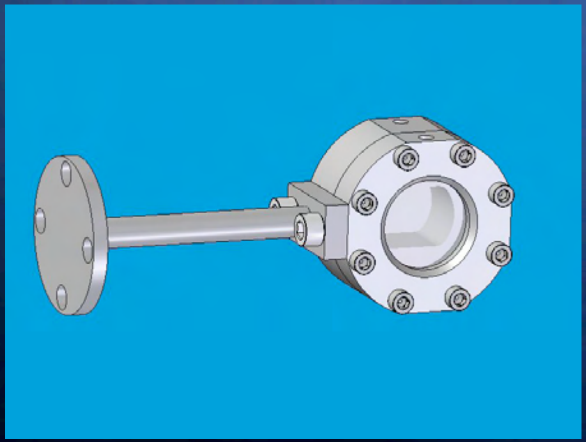
- Signature at low energy
- Moderate beam size
- Use YAG, better than OTR at this energy

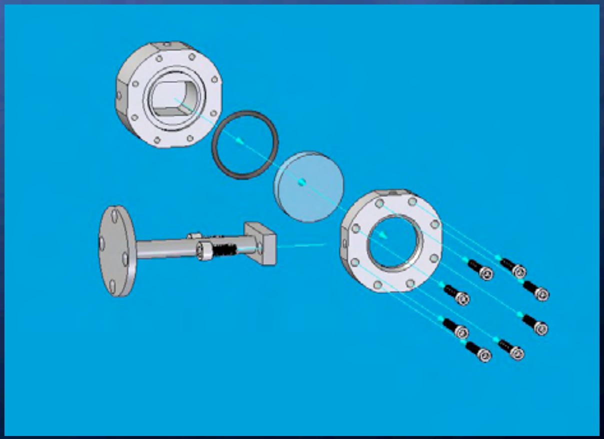
Diagnostics 2: Longitudinal

- Photon based
  - Detector: streak camera
  - Detector: laser gated, multi-shot
  - CTR autocorrelation
- Beam based (high energy)
  - Momentum spectrum
  - RF deflector
  - Zero-phasing

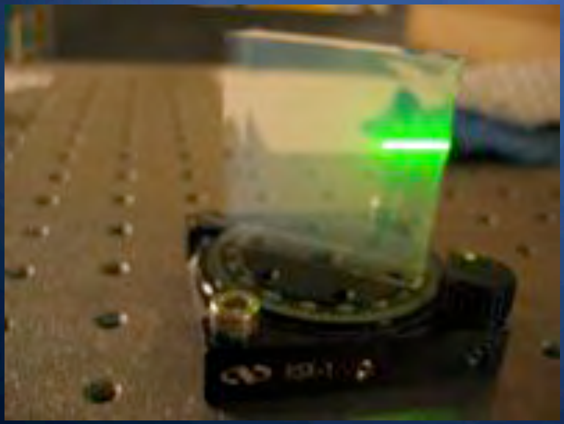
Diagnostics 3: Creating photons

- Aerogel-based Cerenkov cells
  - At 5 MeV threshold is n=1.005
  - Low index (n=1.007-1.02), "small" angle (3.5-9.5 deg)
- Holder protects aerogel from vacuum
  - Building for SLAC/SPARC at UCLA
- Multiple scattering upstream (150 μm Al)
  - 4.7 degrees at 5 Mev
  - Limits length of material for imaging? Depends on n



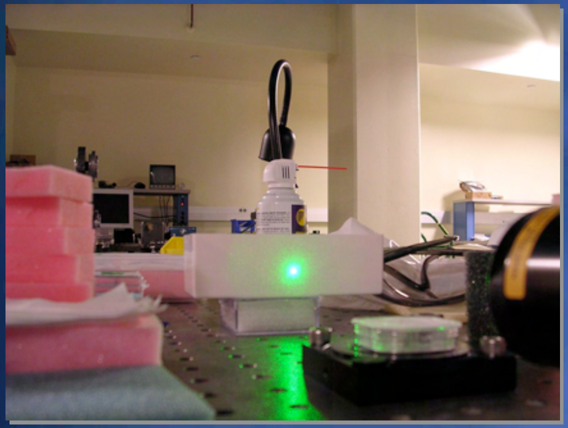


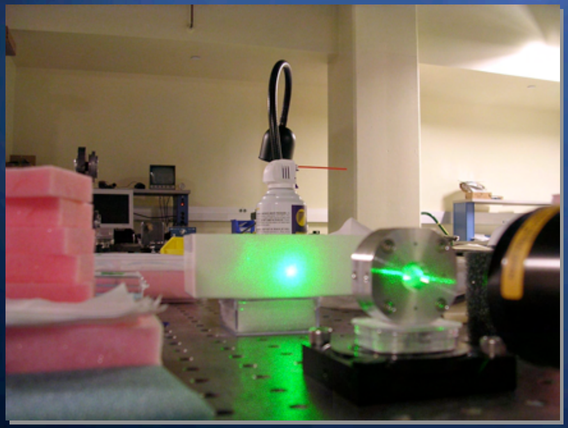
Aerogel measurement: refractive index



- Measurement of refractive index by refraction
- Sample: *n*=1.018
- We would like smaller…
- Not trivial - need flat samples to ease cutting requirements

Aerogel measurement: scattering



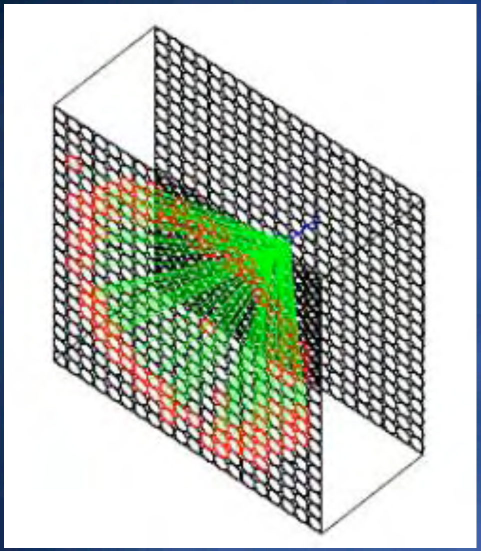


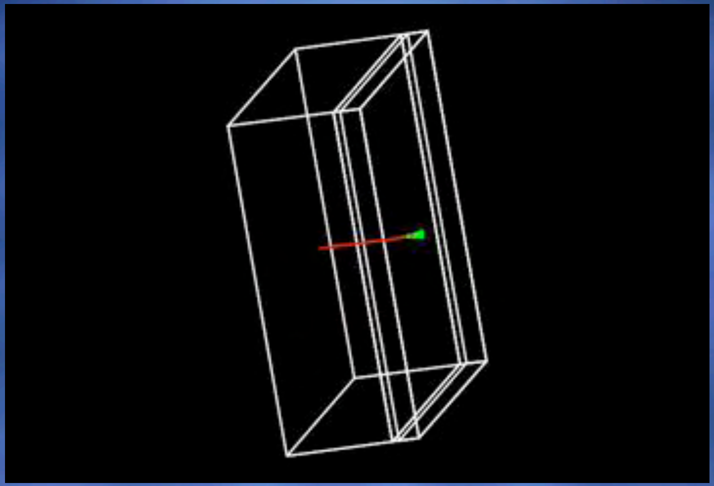
- Optical photons diffuse in angle due to scattering
- Should be similar to Cerenkov angle
- OK!

Diagnostics 4: Using photons

- Streak camera
  - Slit normal to streak direction
  - Pulse profile in *t*
  - Full image in *x-t* ?
  - Need best possible version (0.25 ps resolution)
- Laser gating (Musumeci…)

GEANT simulations

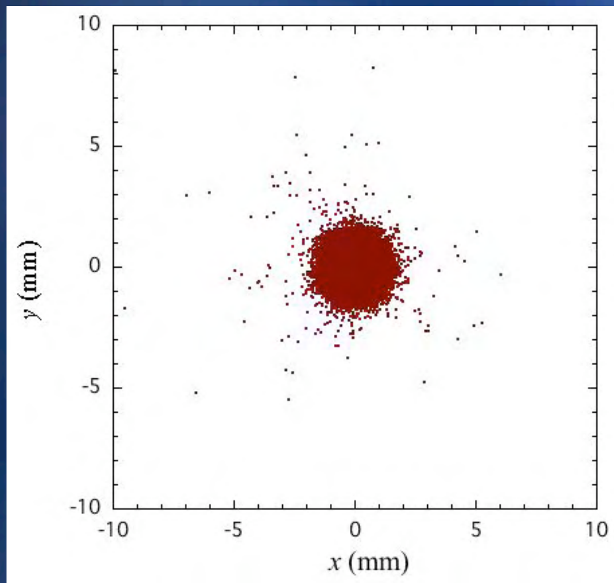


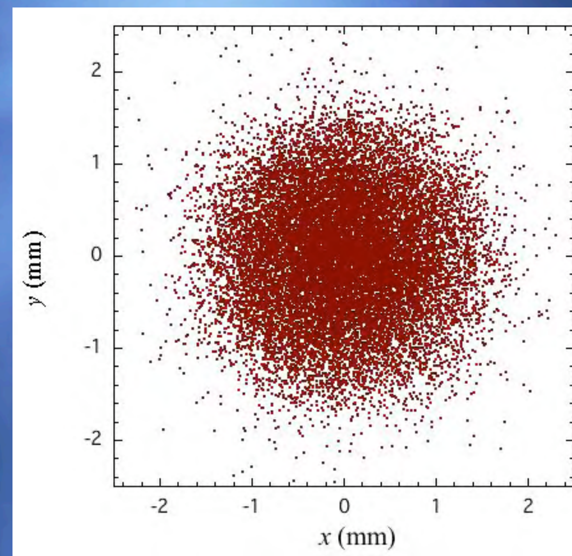


STE simulations by:
M. Dunning, A. Cook, J. Rosenzweig

- Optical Cerenkov radiation simulation by GEANT, pioneered by Dirk Lipka (BESSY)
- Simulate scattering, CR photon characteristic
- Example Aerogel thickness=6.0 mm, Al thickness=20um, n=1.03
- Particles from PARMELA (STE)

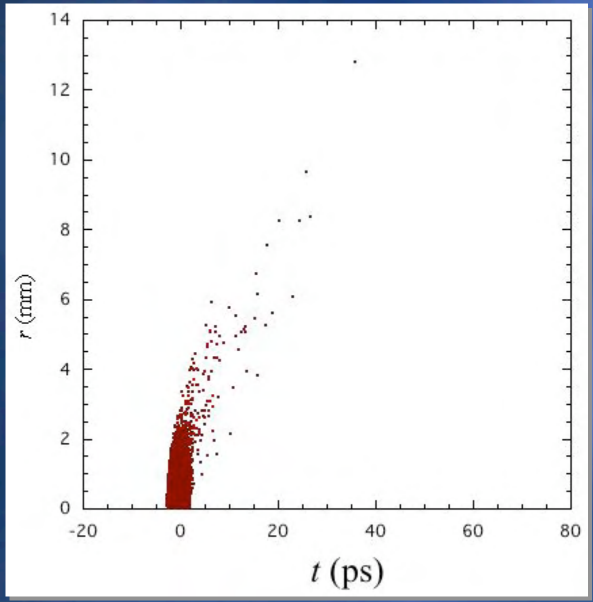
GEANT derived images

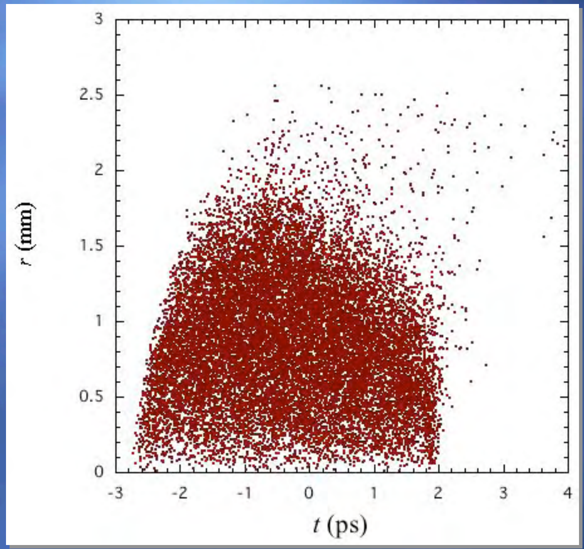




- Aerogel thickness=2.0 mm, Al thickness=150 um, n=1.02
- 19,100 photons, 50,000 electrons (PARMELA)
- 10% BW cut

GEANT time-resolved images

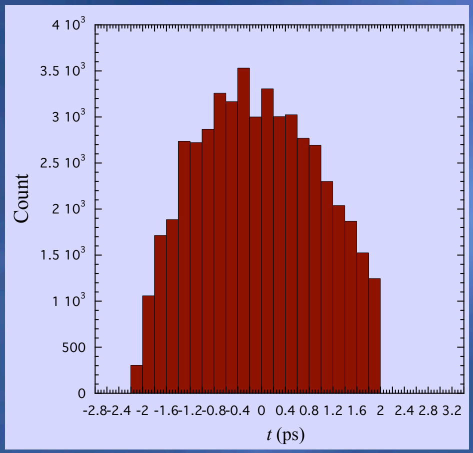


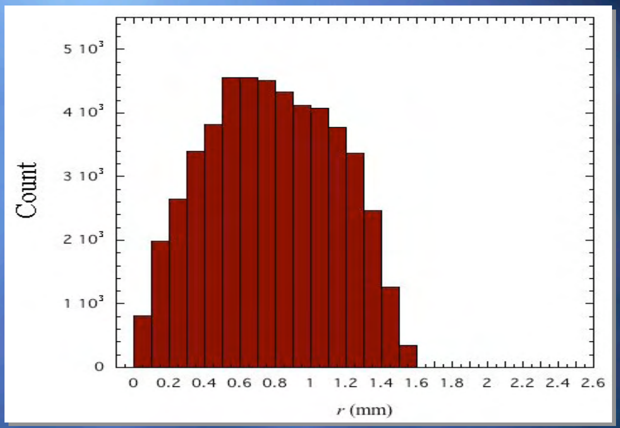


- Aerogel thickness=2.0 mm, Al thickness=150 um, n=1.02
- 19,100 photons, 50,000 electrons (PARMELA)
- 10% BW cut (exactly as expected)
- Large tails

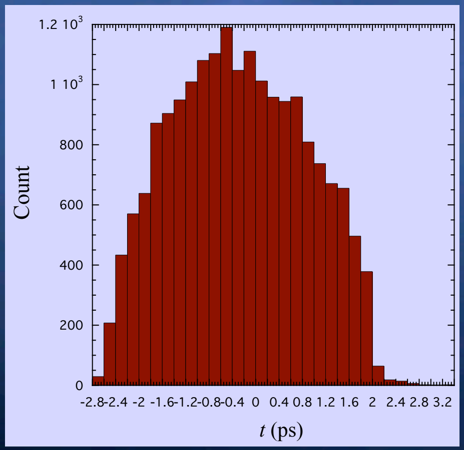
Signatures in projected distributions

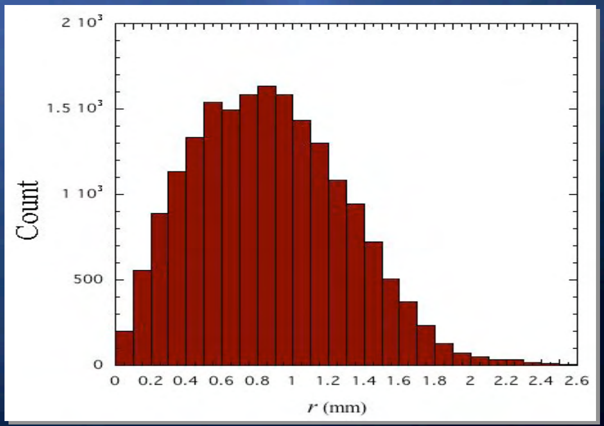
PARMELA e-beam





GEANT photons



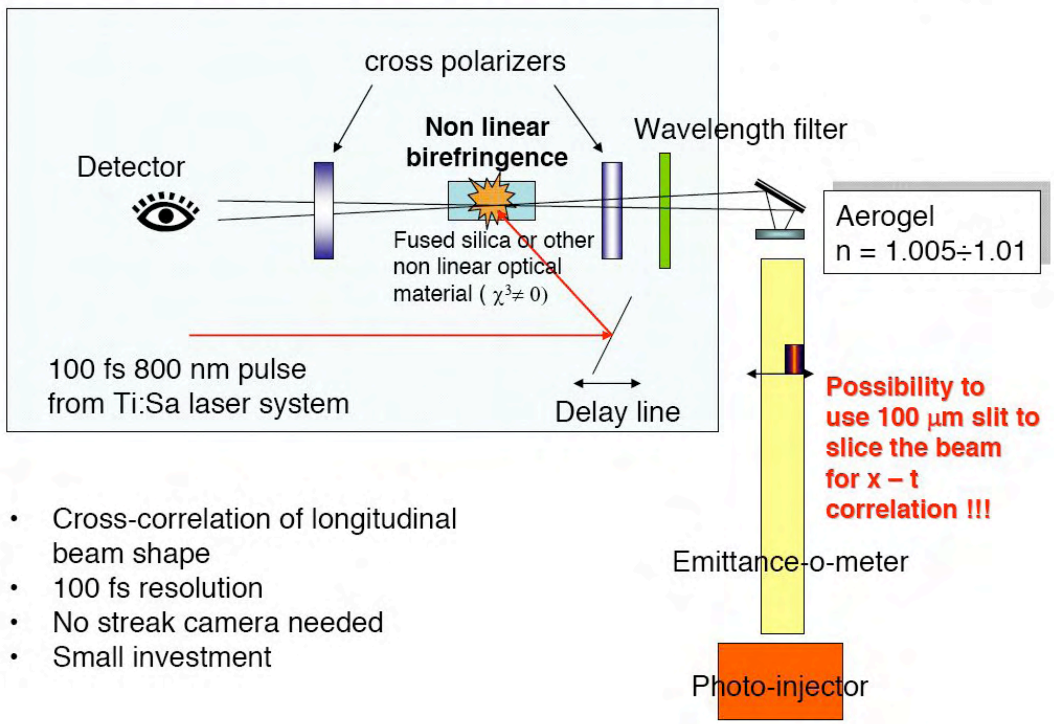


temporal

radial

If you have no streak camera, you need a new idea…

Polarization gating of Cherenkov Radiation

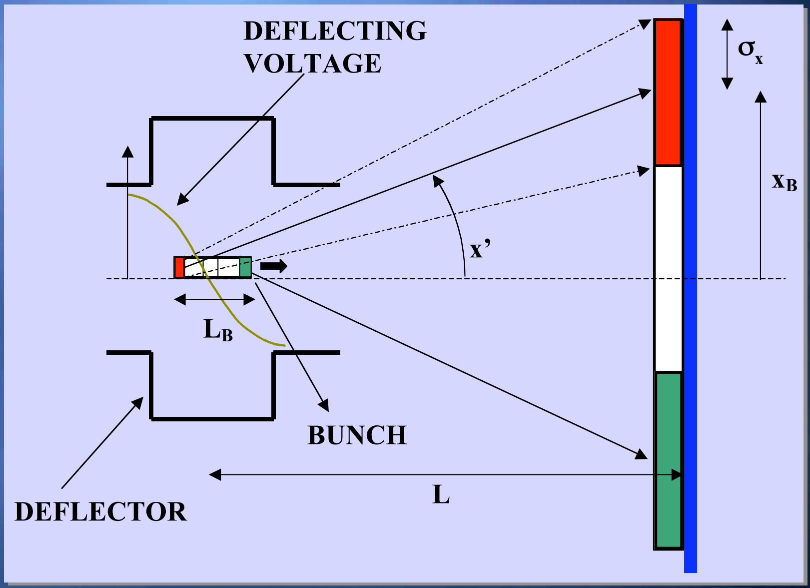


- Cross-correlation of longitudinal beam shape
- 100 fs resolution
- No streak camera needed
- Small investment

Courtesy P. Musumeci

If you have no streak camera, use an RF deflector

- Only at high energy?
- Beam has "collapsed" transversely…
- Very high resolution!



Conclusions

- Intense interest in this idea around the photoinjector community
- Experiments somewhat challenging, but not outside state of art
  - A few good sites…
- Lets do one here?

FORSE ITALIA

Sì!