STELLA
Staged Electron Laser Acceleration

STI OPTRONICS

Laser Wakefield Acceleration Driven by a CO_2 Laser (STELLA-LW)

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ATF Users' Meeting
Jan. 8, 2004

Work was supported by the U.S. Department of Energy, Grant Nos. DE-FG03-98ER41061, DE-AC02-98CH10886, and DE-FG03-92ER40695

Outline

- Background
- Review theory behind experiment
- Describe proposed experiment and predictions
- Review experimental plans
- Review program organization, collaborators, and schedule
- Conclusions

Background

- STELLA program successfully demonstrated important capabilities relevant to laser accelerator systems
  - Staging of microbunches and rephasing with optical wave
  - Monoenergetic acceleration of microbunches
  - High trapping efficiency

- STELLA used inverse free electron laser (IFEL) for convenience
  - Device is well understood, relatively easy to control
  - Has inherent scaling limit, process becomes inefficient at high γ

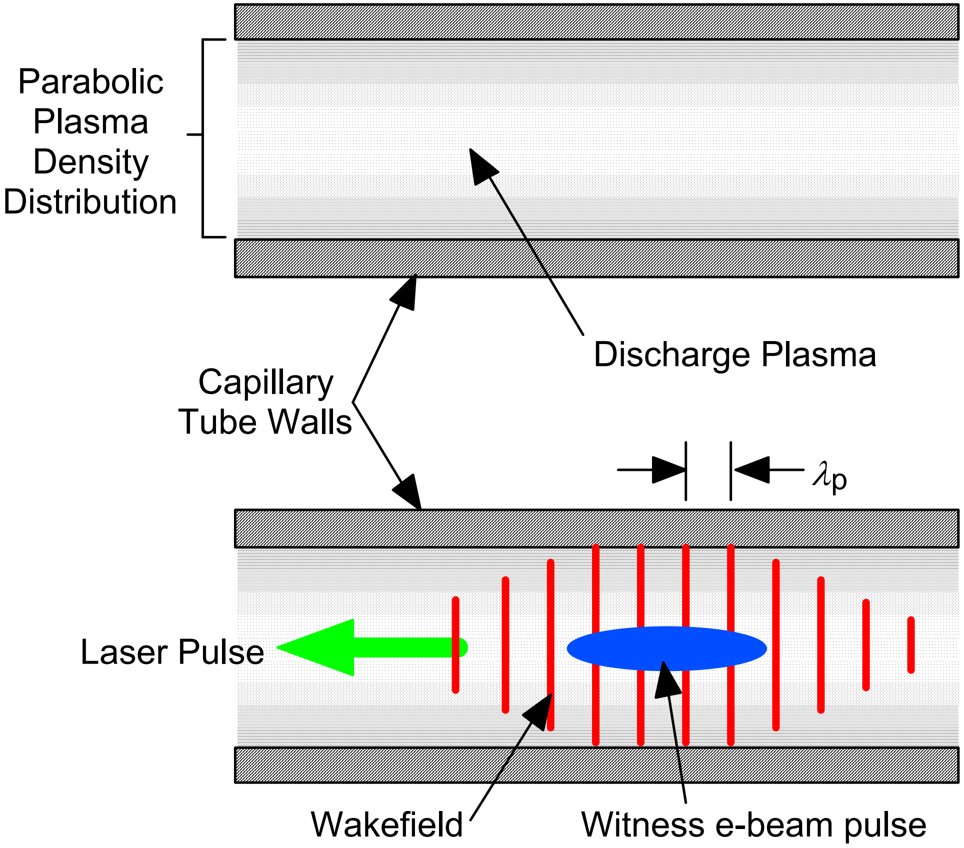
- STELLA approach can be applied to other laser acceleration mechanisms
  - Modulate *e*-beam to create microbunches
  - Trap and accelerate microbunches in stages

Laser Wakefield Acceleration (LWFA) Will be Emphasis of Next Program

- Laser wakefield acceleration (LWFA) is more scalable method
  - Gradients >1 GV/m demonstrated
  - Most experiments done using near-IR lasers, none at 10.6 μm
- Propose to apply STELLA approach to LWFA
  - Would be first to demonstrate LWFA driven by CO_2 laser beam
  - Call new program: STELLA-LW (short for laser wakefield)

Laser Wakefield Acceleration (LWFA) in Capillary Discharge

- Different plasma sources possible for LWFA
  - Capillary discharge chosen for STELLA-LW
  - Already demonstrated at ATF
- Parabolic plasma density guides laser beam
- Laser pulse excites wakefield
- Witness *e*-beam pulse energy modulated by wakefield



Resonant vs. Self-Modulated LWFA

- In resonant LWFA, the laser pulse length τ_L is related to plasma wavelength λ_p by:

  $$\tau_L \sim \lambda_p/2c$$

  where c is speed of light

- In self-modulated LWFA (SM-LWFA), $\tau_L >> \lambda_p/2c$
  - Enhances growth of wakefield via stimulated Raman scattering (SRS)
  - Much higher gradients than resonant LWFA possible
  - Very nonlinear process, which may make control of wakefield difficult

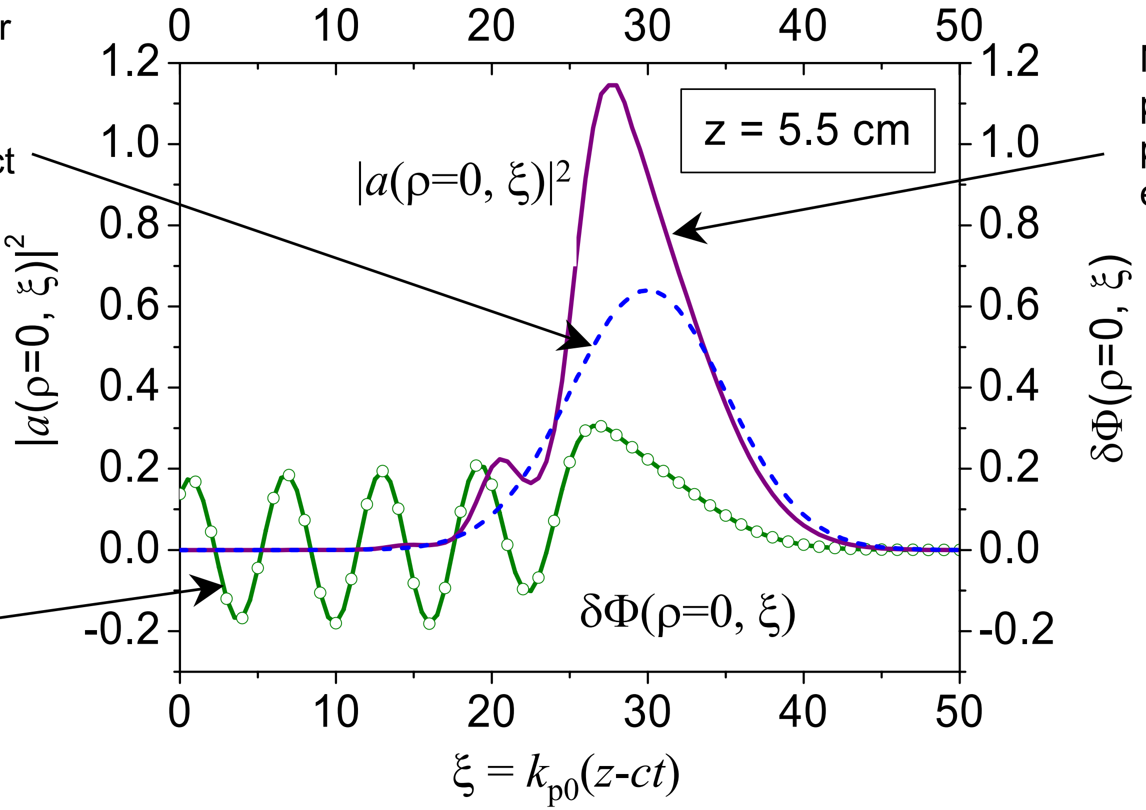
- For ATF TW CO_2 laser beam 2-ps pulse length:
  - $\lambda_p = 1.2$ mm $\Rightarrow n_e \sim 8 \times 10^{14}$ cm^{-3}
  - 2-ps is too long for resonant LWFA, but too short for SM-LWFA

Pseudo-Resonant LWFA

- Existing LWFA code modified during STELLA program to model high-intensity short-pulse (2 ps) CO_2 laser beam
  - Work done by N. Andreev, *et al*.
- Discovered “pseudo-resonant” wakefield generation regime
  - Good wakefield possible even though laser pulse length too long for resonant LWFA and too short for self-modulated LWFA
  - Possible because pulse steepening occurs due to:
    - stronger self-focusing in the middle (maximum) of the laser pulse
    - Partial self-modulation on trailing edge of pulse
  - Effect independently uncovered by Z. Najmudin, *et al*., (“Forced LW”)
- In model simulation, 2-ps pulse effectively acts like 0.5-ps pulse
  - Can operate at $n_e = 1 \times 10^{16}$ cm^{-3}, which is density for 0.5-ps pulse
  - Good wakefield generation possible (~1 GV/m) despite being off-resonance by 4×

LWFA Model Simulation for STELLA-LW

- Assume 2-ps, 5-J ATF CO_2 laser pulse drives wakefield
- Electron plasma density on axis is $n_e = 1.1 \times 10^{16}$ cm^{-3}
- Conditions 5.5 cm into plasma



Normalized laser pulse intensity <u>without</u> pulse steepening effect

Normalized laser pulse intensity <u>with</u> pulse steepening effect

Wakefield Potential δΦ

LWFA at 10.6 μm has Other Advantages

- Laser field parameter a scales as λ
  - Ponderomotive potential scales as a^2 (equivalent to λ^2)
  - For same focus size, 10-μm light gives 100× higher potential than 1-μm light
  - Can focus 1-μm light tighter to compensate, but also requires undesirable tighter *e*-beam focus

- Wakefield damping time $\propto n_e^{-1}$
  - $n_e = 1 \times 10^{16}$ cm^{-3} implies relatively long damping time (>100 ps)
  - Provides plenty of time to intersect witness electron pulse with wakes

- 10^{16} cm^{-3} is well below critical density for absorption of IR light

- Relatively long plasma wavelength (>300 μm) may also help ease synchronizing with LWFA-generated microbunches in future experiments

Overview of STELLA-LW Experiment

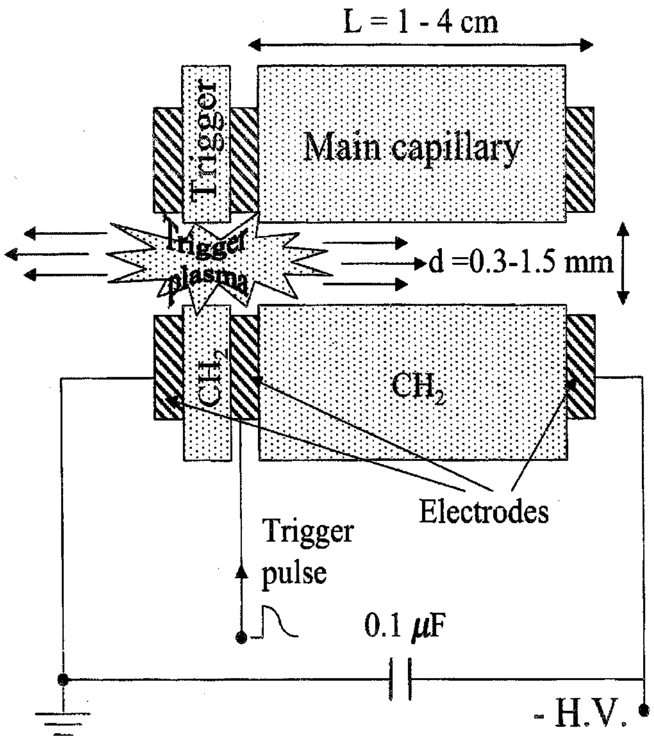
- Phase I Program (being considered in this current proposal)
  - Demonstrate LWFA at 10.6 μm inside capillary discharge
  - For 1.2 cm long plasma length, predict ~7-8 MeV energy gain
- Possible future phases of Program (not part of this current proposal)
  - Demonstrate microbunching using LWFA buncher
  - Demonstrate staging between LWFA buncher and LWFA accelerator
  - Demonstrate high-trapping efficiency, monoenergetic acceleration
- Long-term goal of Program
  - Demonstrate $\geq$100-MeV energy gain using CO_2-laser-driven LWFA
  - Accelerate $\geq 5 \times 10^8$ electrons with narrow energy spread
  - Addresses challenge given by D. Sutter in 1992 AAC Workshop

Description of STELLA-LW Phase I Experiment

- Task 1 (Year 1): Build capillary discharge system
  - Based upon ATF capillary discharge design first developed by A. Zigler
  - Need to generate relatively low plasma density (~10^{16} cm^{-3})
  - Will be scalable to longer lengths
- Task 2 (Year 2): Demonstrate wakefield generation at 10.6 μm
  - Focus TW CO_2 laser beam into capillary discharge
  - Detect wakefield using coherent Thomson scattering (CTS) diagnostic
  - First time CTS used to diagnose capillary discharge
- Task 3 (Year 3): Demonstrate *e*-beam energy modulation by LWFA
  - Send *e*-beam into capillary after laser pulse
  - Measure energy modulation of *e*-beam

Review of Capillary Discharge Design

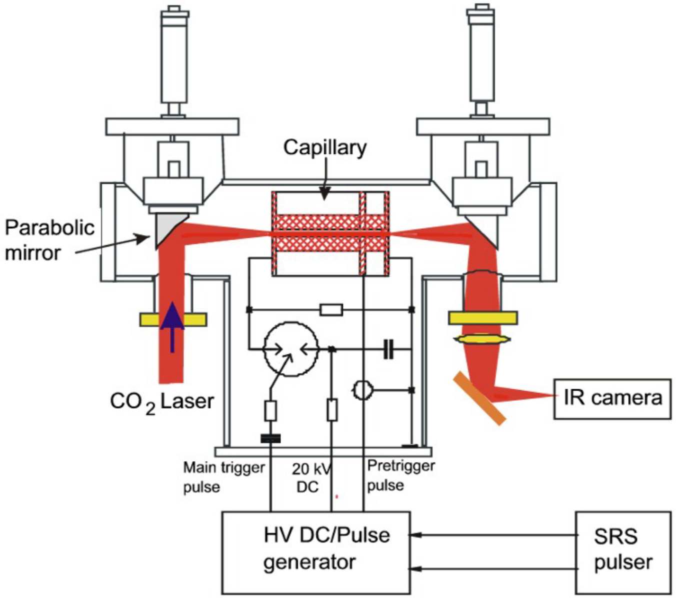
Basic Zigler design [1]

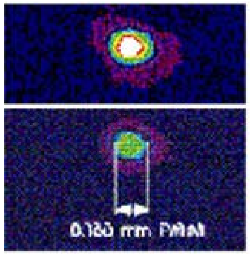


1) D. Kaganovich, *et al.*, Appl. Phys. Lett. **71**, 2925 (1997).

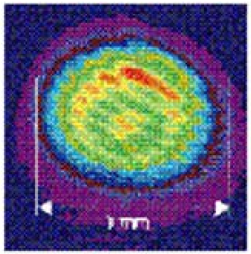
2) I. V. Pogorelsky, *et al.*, Appl. Phys. Lett., **83**, 3459 (2003).

ATF channeling experiment [2]

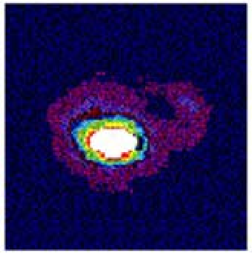




Laser beam at entrance



Laser beam at exit w/o discharge



Laser beam at exit w/ discharge

Capillary Discharge Issues and Plans

- Need 10^{16} cm^{-3} plasma density
  - ATF Channeling Experiment produced 10^{17}-10^{18} cm^{-3} plasma density using 1-mm diameter capillary tube
  - Plasma density scales as IR_{cap}^{-2}, where I is discharge current and R_{cap} is capillary tube inner radius
  - Of order 10^{16} cm^{-3} should be possible if R_{cap} = 1.6 mm
  - At large tube radius potential issues include plasma stability, uniformity, and reproducibility
  - Oxford U. used H_2 inside ceramic tube, may make easier to achieve low plasma density plus provides other advantages
- First year of STELLA-LW program will concentrate on developing and testing capillary discharge
  - Will make modular, expandable design able to accommodate longer tubes
  - Can probe discharge using low power laser beam

Generation of Wakefield with CO_2 Laser

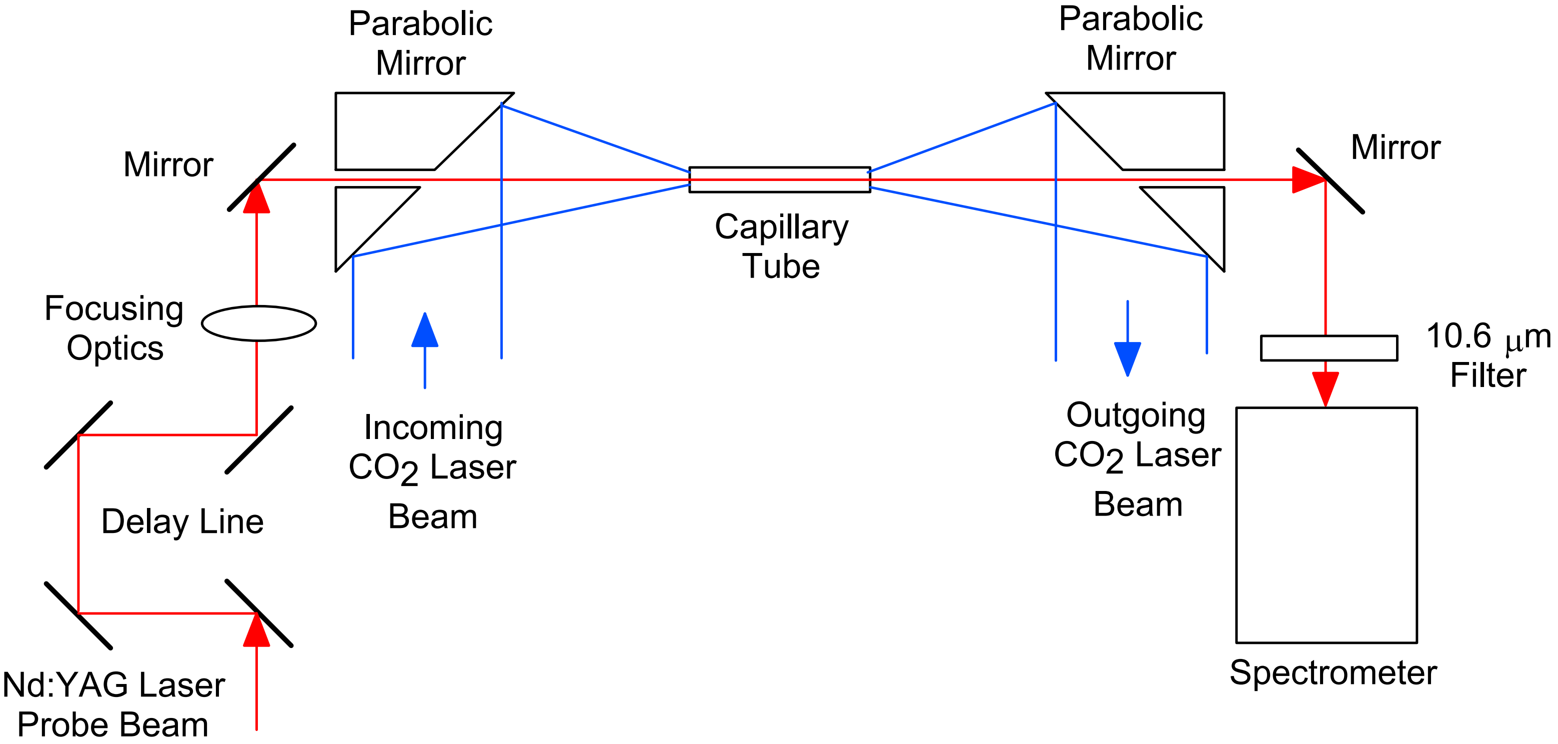
- During 2nd year of STELLA-LW will focus ATF CO_2 laser beam into capillary discharge
  - Need to deliver ≥5 J, 2-ps laser pulse
- STELLA-LW can utilize similar laser beam transport design used by ATF Channeling and Compton Scattering experiments
  - Transport designs are proven and effective
  - Should be less complicated, more stable optical system than STELLA
- Key question is whether good wakefield has been generated
  - Different wakefield diagnostic techniques considered
  - Chose coherent Thomson scattering (CTS)
  - Amplitude and plasma density can be determined using CTS
  - Model predicts large amplitude waves appropriate for CTS detection
  - STELLA-LW will be first to use CTS on capillary discharge

Review of Coherent Thomson Scattering

- In coherent Thomas scattering (CTS), a probe beam is sent either along or across the plasma discharge
  - Probe beam can be different wavelength than pump beam, which helps eliminate noise from the pump beam
  - Plasma wave acts like a grating and scatters probe beam light
  - Generation of anti-Stokes (AS) light corresponds to wakefield traveling near speed of light
  - AS-light directed in forward direction corresponds to wakefield useful for accelerating electrons
- CTS used extensively by others (e.g., UCLA, NRL)
  - A. Ting (NRL) is expert on CTS and is collaborator on STELLA-LW

Possible CTS Arrangement for STELLA-LW

- Utilize 1.06-μm laser beam used to drive ATF photocathode as probe beam
- Look for anti-Stokes signal emitted collinear with probe beam
- Expect ~3.3 nm shift from fundamental at $n_e = 10^{16}$ cm^{-3}

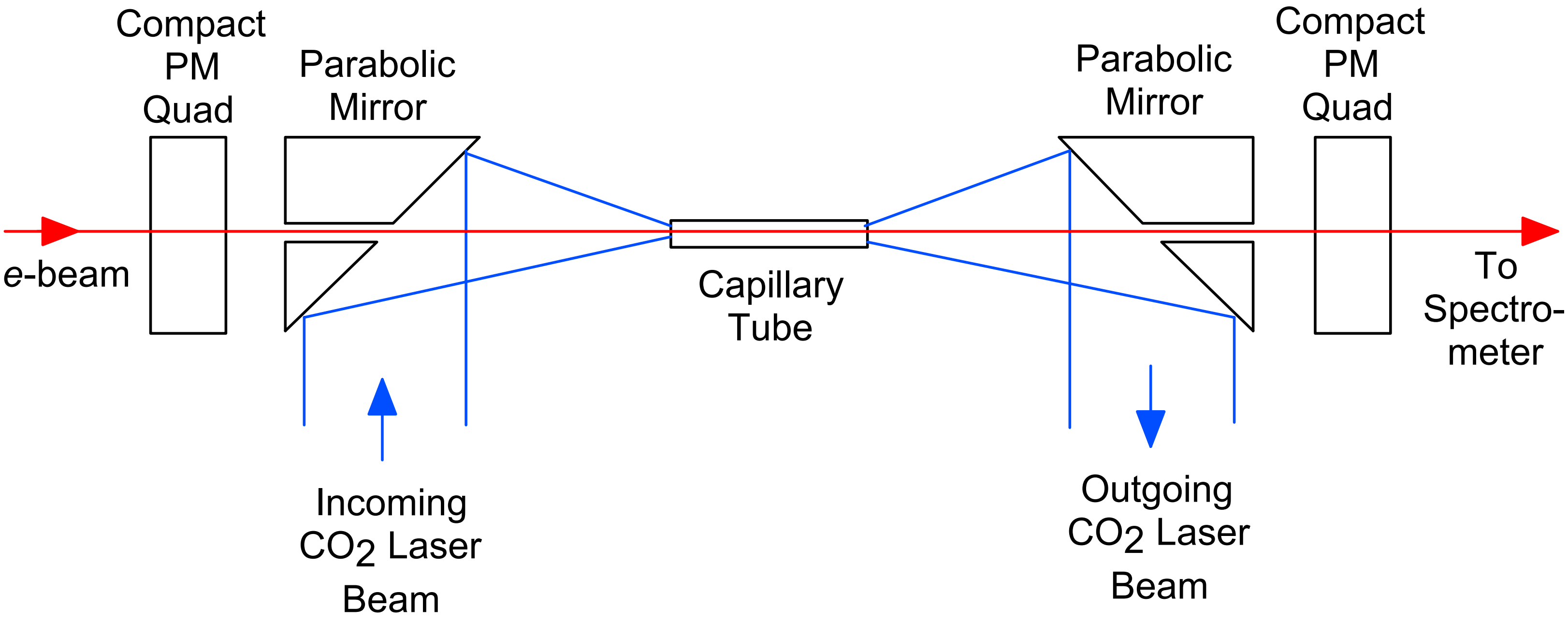


Energy Modulation by LWFA

- During 3rd year, will send *e*-beam through wakefield inside capillary discharge
- Important to preserve *e*-beam quality during interaction
- Strong radial focusing forces exist in wakefield
  - Can avoid focusing by keeping *e*-beam diameter small
  - Model indicates *e*-beam diameter needs to be ≤40 μm
  - During Compton Scattering Experiment, *e*-beam spot size of ≈15 μm rms demonstrated
    - Used fixed-strength, short-focal-length, permanent-magnet (PM) quad
- STELLA-LW beamline system will be designed to permit tight *e*-beam focusing
  - STI manufactures <u>variable</u>-strength, compact PM quads
  - Will also need good beam position monitors (BPM) to measure *e*-beam size

Integrated STELLA-LW Experiment

- Can use compact permanent-magnet (PM) quad(s) to focus *e*-beam into tube
- Will also include high-resolution BPMs along beamline



Model Prediction for Energy Modulation

- 3-ps *e*-beam pulse (equivalent to ≈1 mm length) overlaps several wakefield periods (~300 μm)
  - Expect modulation of *e*-beam energy
- Parameter values assumed in model prediction
  - *E*-beam energy = 45.6 MeV (not optimized yet)
  - *E*-beam transverse size, σ_r = 25 μm
  - Laser pulse length = 2 ps
  - Laser pulse energy = 5 J
  - Plasma discharge length = 1.2 cm (not optimized yet)
  - **Predict peak energy gain of ~7-8 MeV**

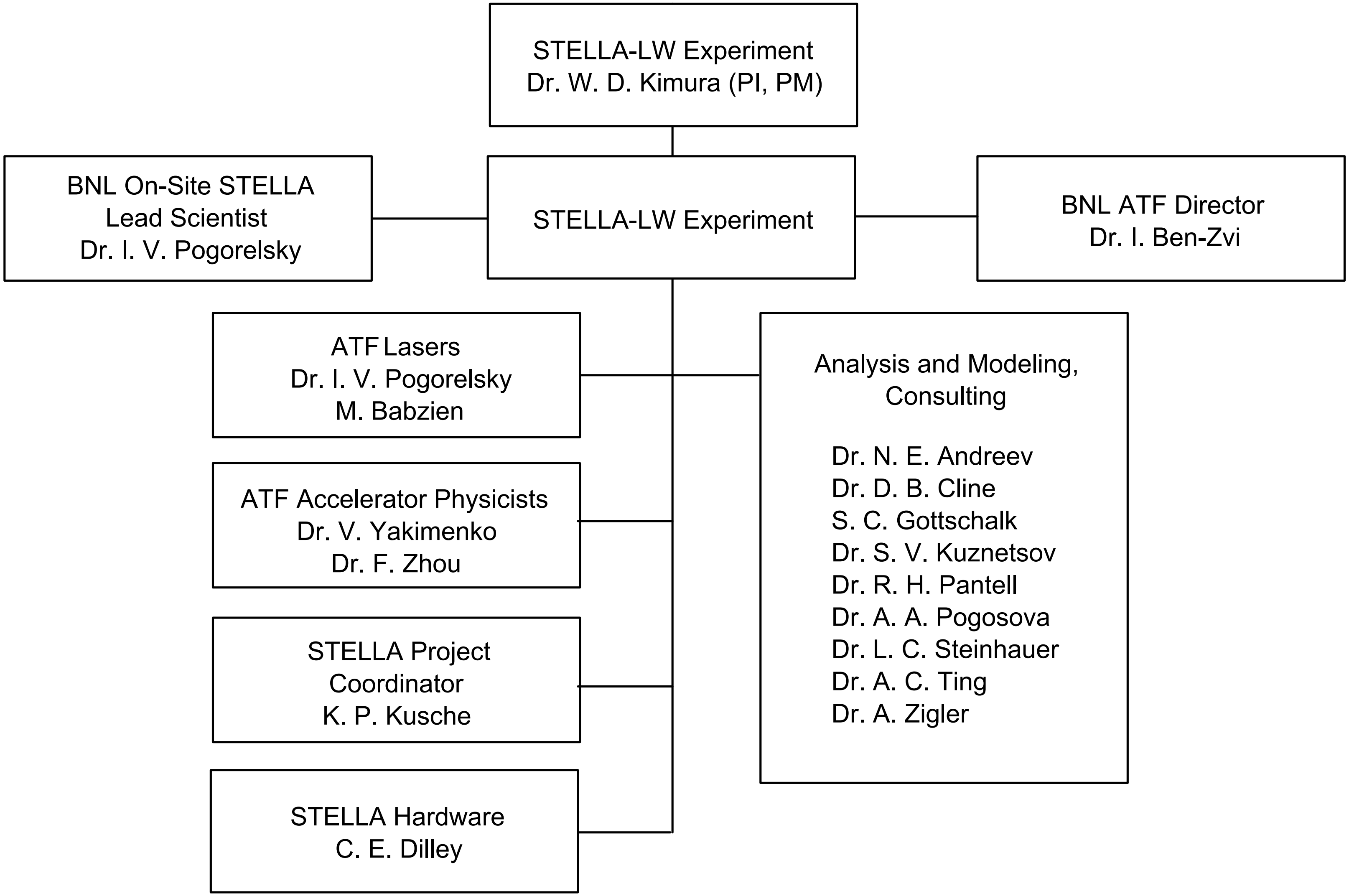
Other Experimental Issues

- Accurate measurement of laser power delivered to plasma important
- ATF has autocorrelator capable of measuring 2-ps pulse length
  - Enables more direct measurement of pulse length than possible during STELLA
- Different means will be explored to improve real-time measurement of laser pulse energy
  - Photoacoustic detector attached to back of mirror within laser system
  - Monitoring reflected light from CO_2 laser amplifier window
  - Monitoring reflected light from input window of capillary discharge chamber
  - Monitoring light transmitted through capillary tube

LWFA/Capillary Discharge Experts Part of STELLA-LW Collaboration

- LWFA theory and modeling
  - Prof. Nikolai Andreev (Russian Academy of Sciences)
  - Dr. Sergey Kuznetsov (Russian Academy of Sciences)
  - Dr. Alla Pogosova (Russian Academy of Sciences)
- LWFA theory and experiments
  - Dr. Antonio Ting (Naval Research Laboratory)
- Capillary discharges
  - Prof. Arie Zigler (Hebrew University)
- Plasma physics and laser acceleration theory
  - Dr. Loren Steinhauer (Redmond Plasma Physics Laboratory)

STELLA-LW Program Organization



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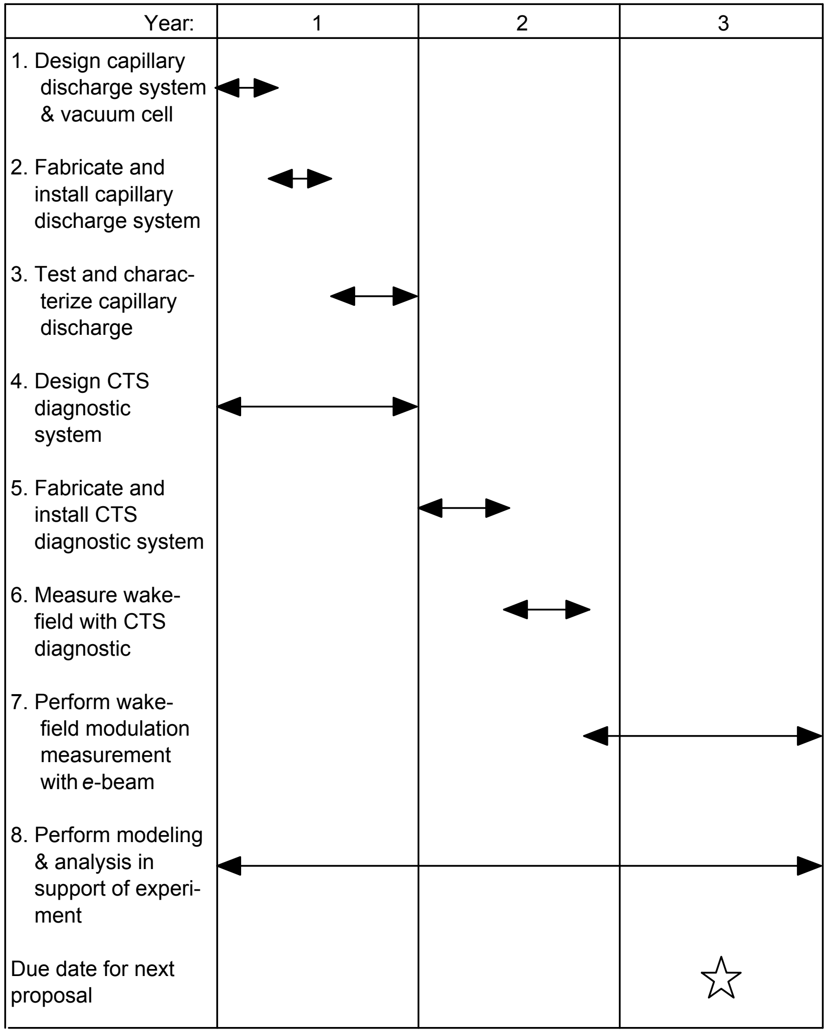
STELLA-LW Program Schedule



1. Design capillary discharge system & vacuum cell
2. Fabricate and install capillary discharge system
3. Test and characterize capillary discharge
4. Design CTS diagnostic system
5. Fabricate and install CTS diagnostic system
6. Measure wakefield with CTS diagnostic
7. Perform wakefield modulation measurement with *e*-beam
8. Perform modeling & analysis in support of experiment

Due date for next proposal

Conclusions

- STELLA-LW experiment will apply the STELLA basic approach to laser wakefield acceleration
  - STELLA-LW collaboration represents a strong, well-balanced team
  - ATF has already demonstrated key components of experiment
- STELLA-LW (Phase I) will be first to:
  - Demonstrate LWFA driven by a CO_2 laser beam
  - To use CTS on a capillary discharge
  - To operate at ~10^{16} cm^{-3} plasma density in a capillary discharge
- STELLA-LW (Phase I) will lay foundation for more advanced LWFA experiments
  - Demonstration of LWFA buncher and generation of microbunches
  - Staging of LWFA devices
  - Ultimately, demonstration of 100-MeV LWFA-driven laser linac