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P 173: Study of the Vishniac Instability and Optically Thin Radiative Blast Waves

Aaron Edens
*Sandia National Laboratories**

Serge Bouquet
CEA-DAM

DE LA RECHERCHE À L'INDUSTRIE

National Nuclear Security Administration

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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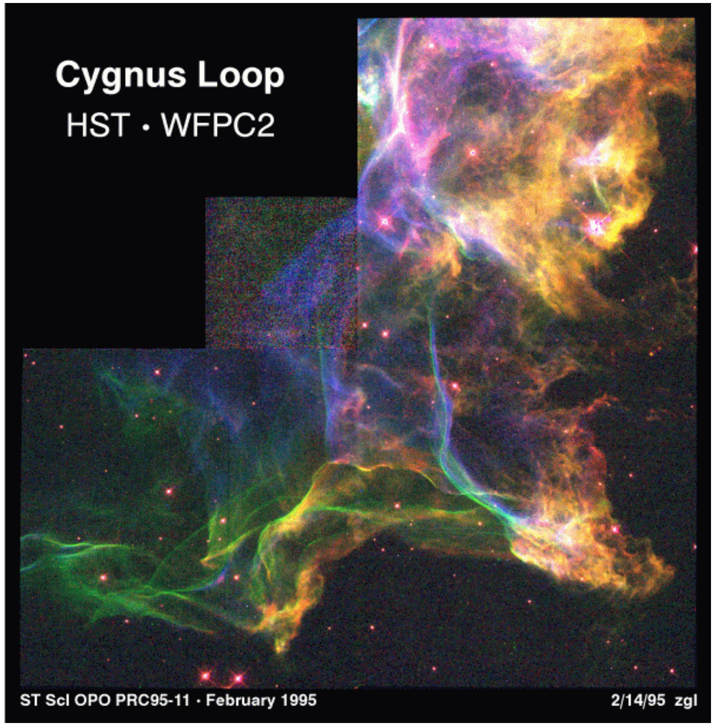
Astrophysical context

Radiative supernova remnants (SNR's) arise after the explosion of a star (supernova - SN) and they show very complex structures (filaments, clumps …)



Our collaboration seeks to understand the physics of radiative blast waves such as these supernova remnants, and specifically the Vishniac instability

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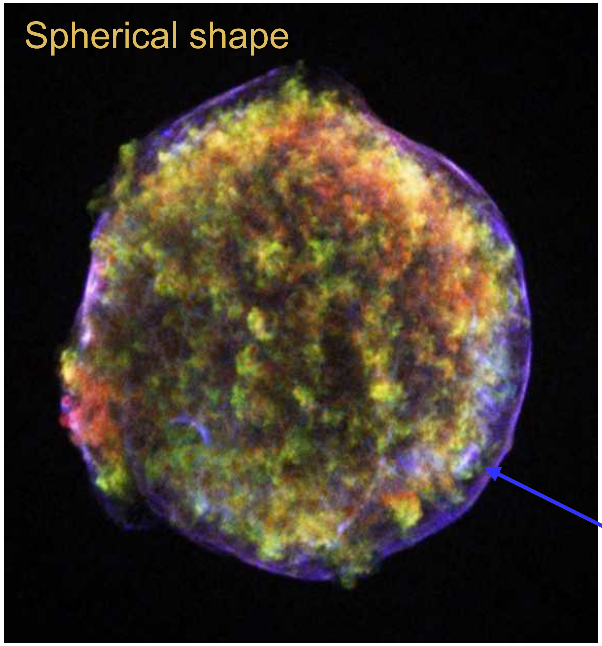
Structure of supernova remnants (SNR) and the physics of radiative blast waves

Tycho (Cass. B, 3 kpc, 441 y.o.)
Young SNR



Spherical shape

Blast wave front

Spikes and bubbles
Rayleigh-Taylor instability (RTI)

Simeis 147 (Taurus, 1 kpc, 30 000 y.o.)
Old SNR

Remaining spherical shape

Credit: Davide De Martin (http://www.skyfactory.org), ESA/ESO/NASA FITS Liberator & Digitized Sky Survey

Pieces of the spherical shell, spherical caps
Vishniac instability (VI)
Late instability - optically thin material
radiation (+ thermal) energy fluxes through the shock front

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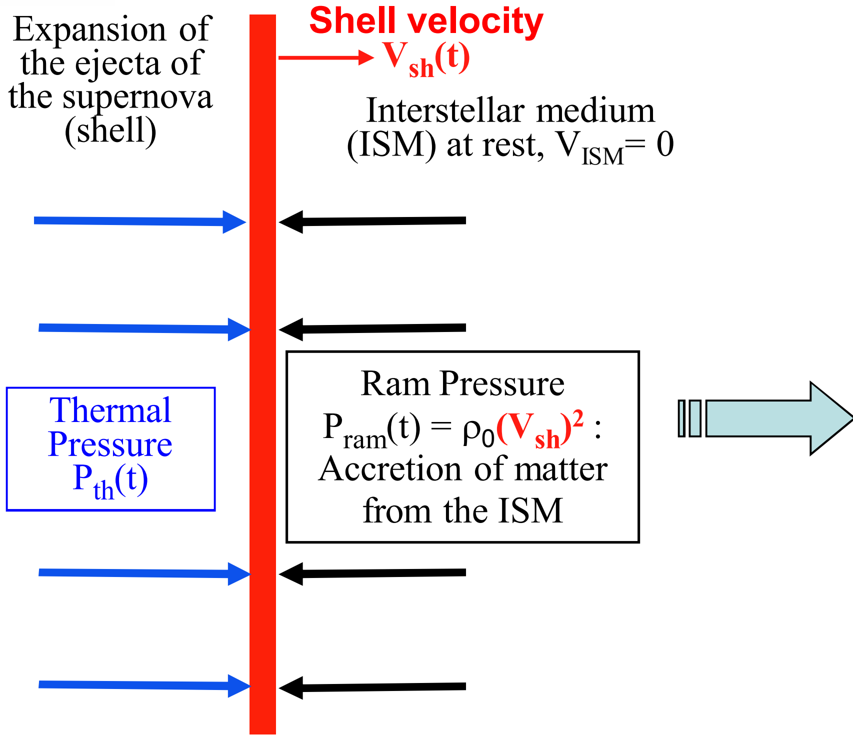
Distortion of the shell (supposed to be thin): Vishniac instability (VI)

Locally, the shell is plane

Thin shell + Blast wave front



Expansion of the ejecta of the supernova (shell)

Shell velocity $V_{sh}(t)$

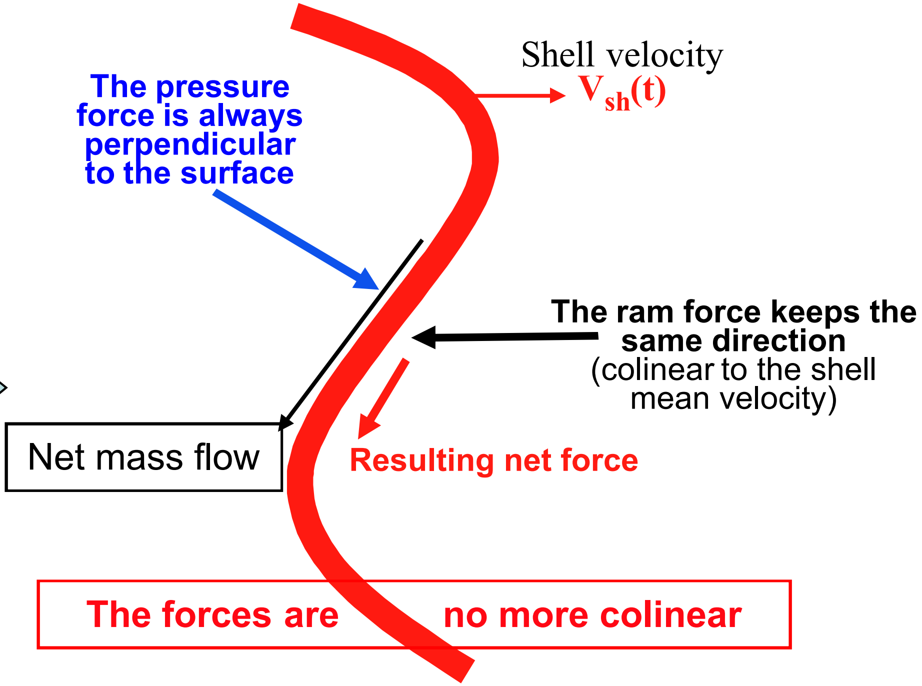
Interstellar medium (ISM) at rest, $V_{ISM} = 0$

Thermal Pressure $P_{th}(t)$

Ram Pressure $P_{ram}(t) = \rho_0 (V_{sh})^2$: Accretion of matter from the ISM

The ram and the thermal forces are colinear (but have not the same magnitude)

The shell is distorted (due to clumps in ISM, for instance)



Shell velocity $V_{sh}(t)$

The pressure force is always perpendicular to the surface

The ram force keeps the same direction (colinear to the shell mean velocity)

Net mass flow

Resulting net force

The forces are no more colinear

Matter flows along and inside the shell

Fragmentation and disruption of the shell and of the shock wave front

(Vishniac instability)

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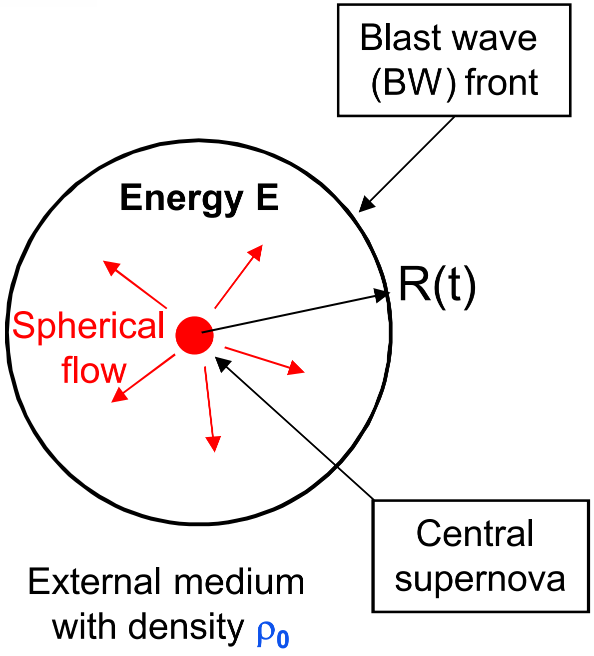
Further than the thin shell approximation: analytic linear perturbation analysis for a spherical flow

Strong point explosion: $R(t) \sim t^{2/5}$



Blast wave (BW) front

Energy E

Spherical flow

R(t)

Central supernova

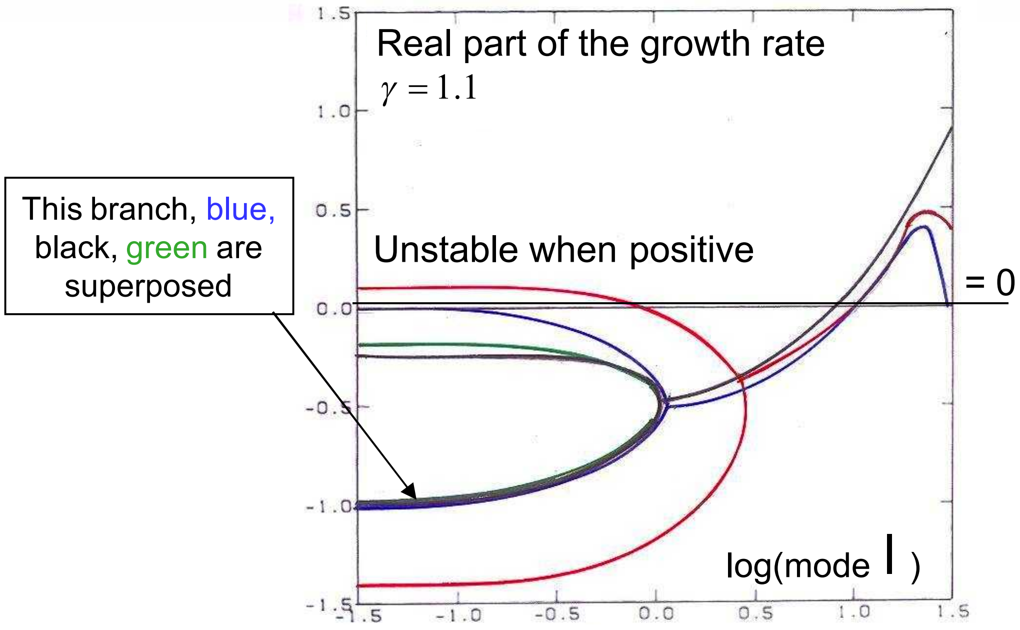
External medium with density ρ_0

Time-dependent radial flow:

$$v(r,t),\ \ p(r,t),\ \ \rho(r,t)$$

Analytic (Sedov, Landau)

Dispersion relations



— Ryu and Vishniac, ApJ (1987), **infinitely thin** shell and $\gamma = 1$ ($\gamma \neq 1$ is not possible)

— Ryu and Vishniac, ApJ (1987), spherical flow

— Kushnir et al., ApJ (2005), spherical flow

— Minière and Bouquet (2013)

No agreement … Stable or unstable ?

Who is right ? Experiments required !

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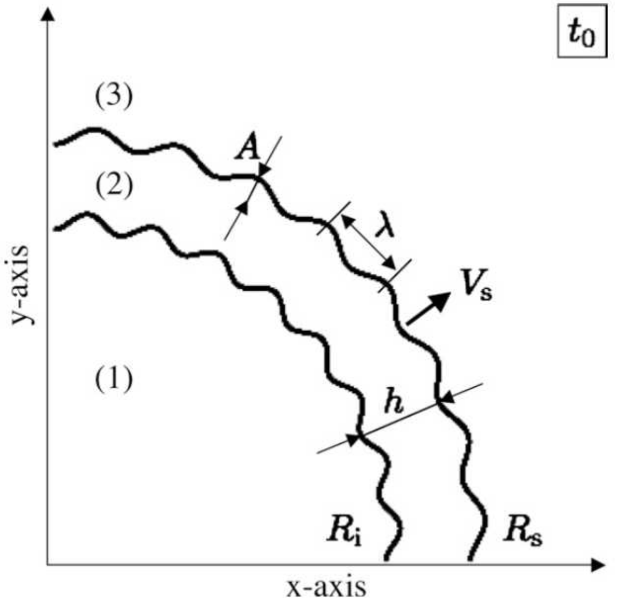
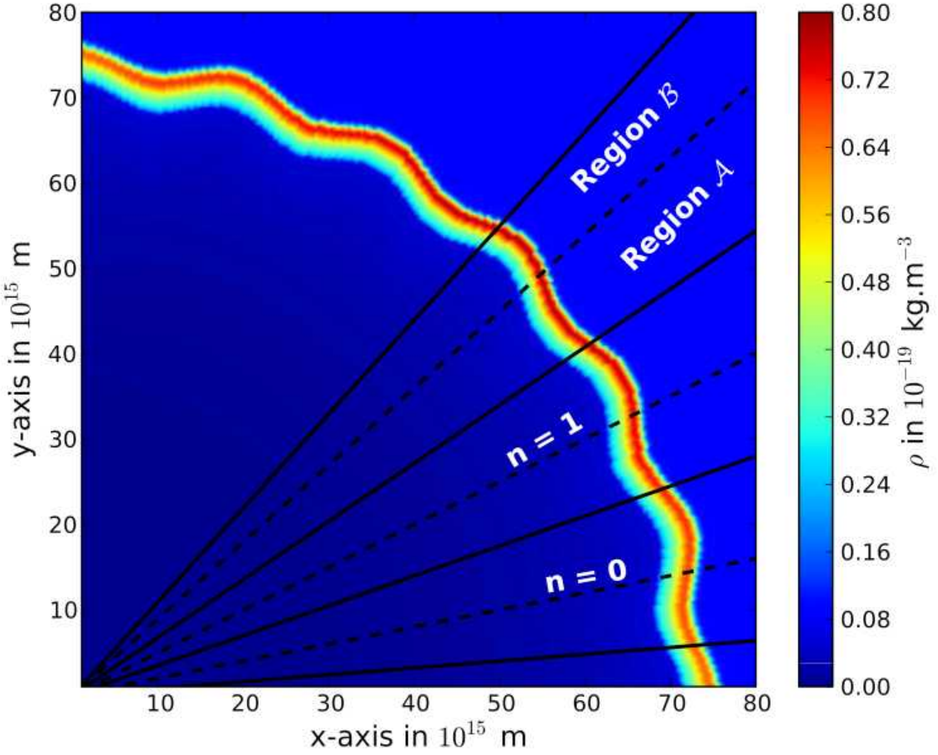
2D-numerical simulations: parallel ripples perpendicular to the vertical symmetry axis

Initial perturbation



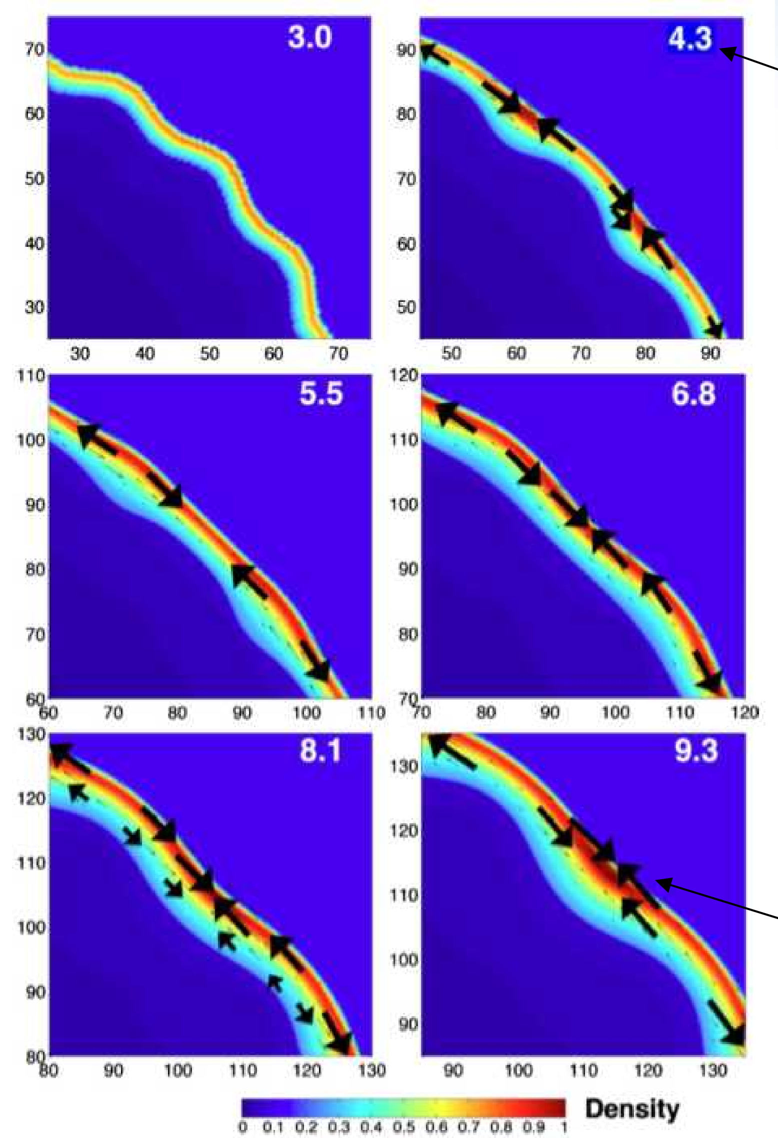
Initial density map $\gamma = 1.1$



$$r_{pert}(t=0) = r(t=0).[1 + A \times \cos(l\,\theta)]$$

$$l = 2\pi R_s / \lambda$$

Linear evolution



Time in kiloyears unit

Spatial scale: 10^{15} m ~ 0.03 parsec

Michaut et al., ApJ (2012)

→ : transverse velocity of the material

An alternation between the overdense regions and the low density zones is observed

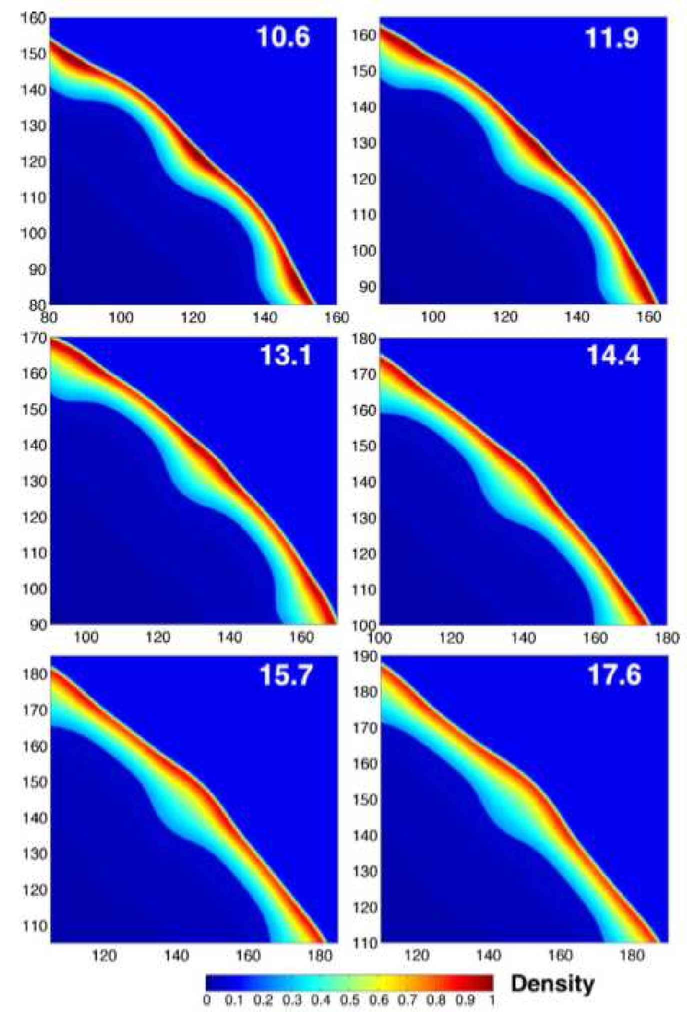
This is the OVERSTABILITY process as described by Vishniac (ApJ, 1983):

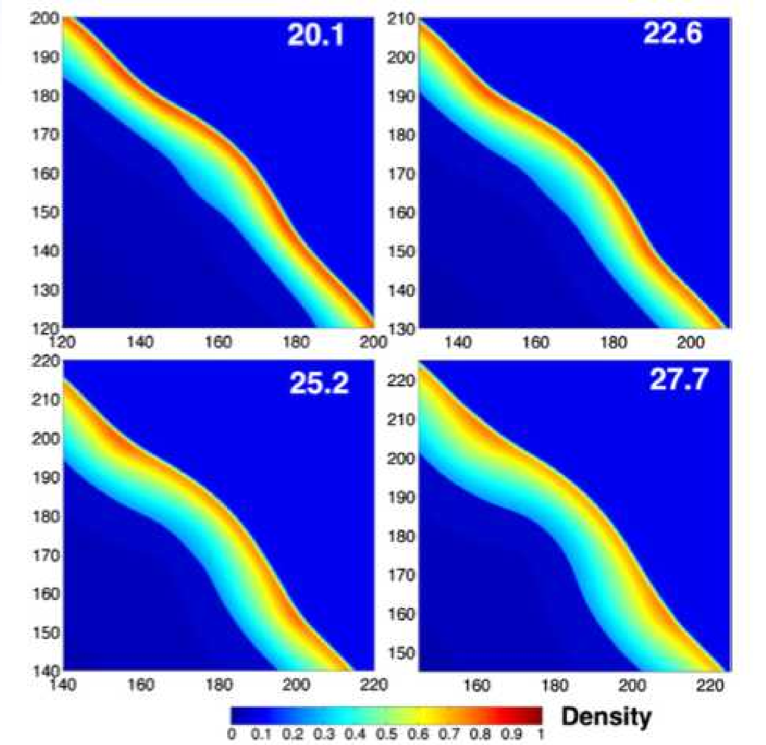
Oscillations with increasing amplitude

The magnitude of the transverse velocity is maximum

Non-linear regime

Time in kiloyears unit, spatial scale 10^{15} m ~ 0.03 parsec

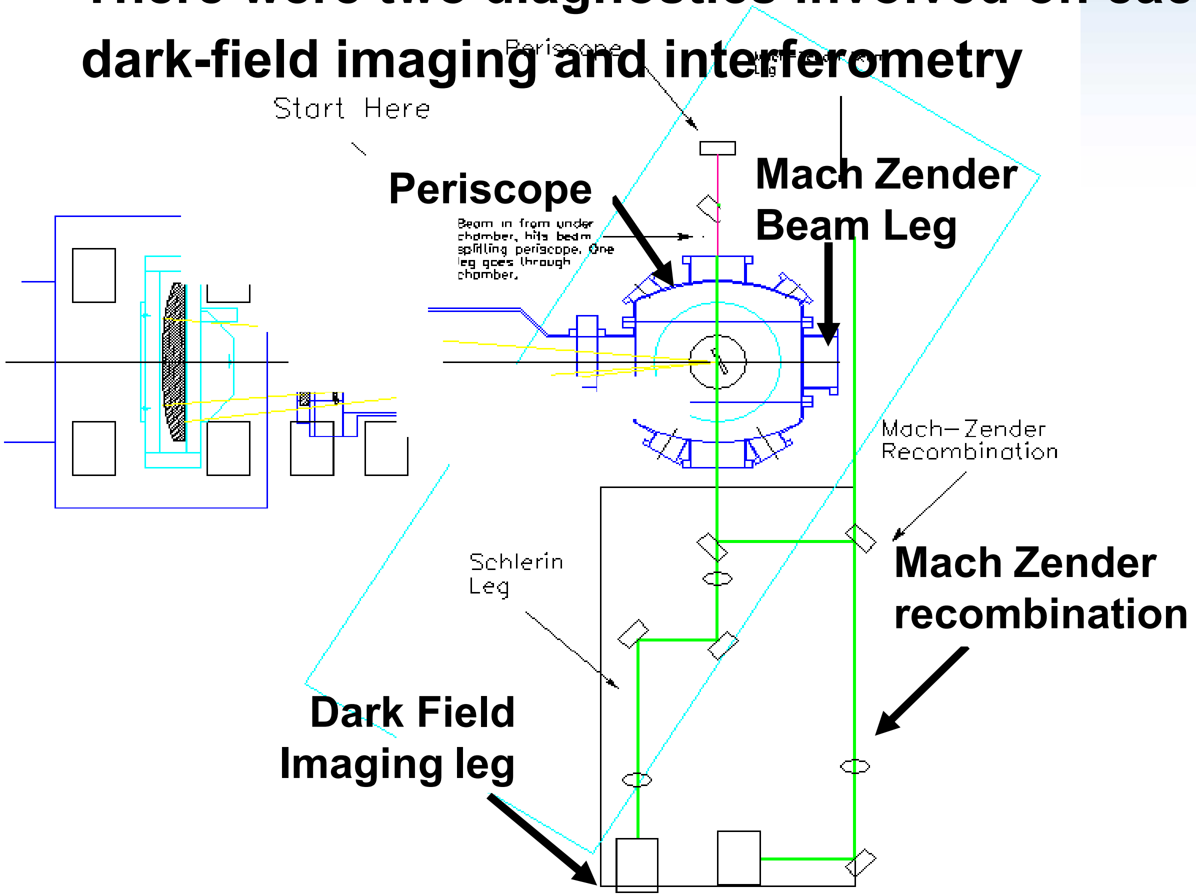




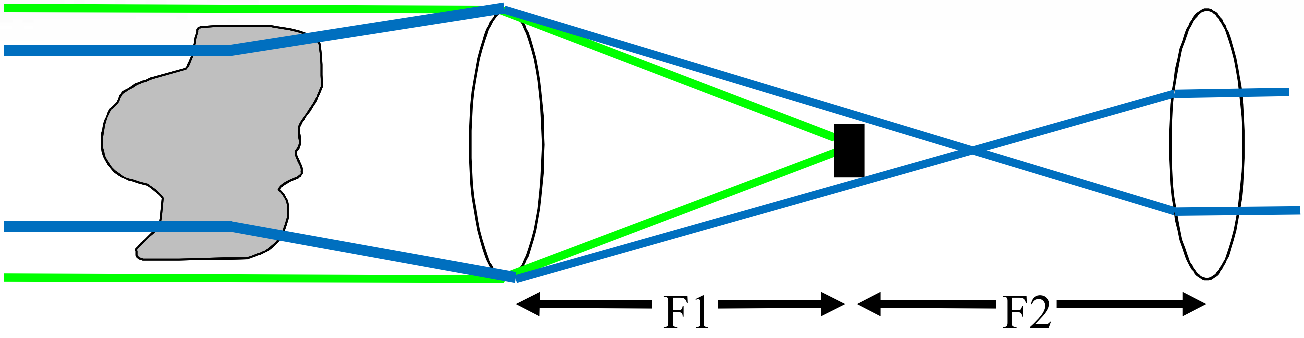
Overdensities are smoothed and the transverse velocity decreases.

The instability is damped …

There were two diagnostics involved on each shot: dark-field imaging and interferometry

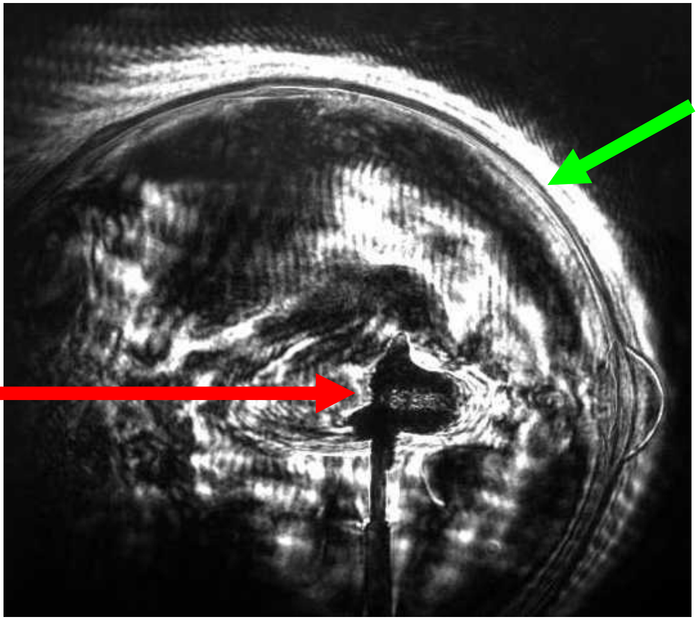


The evolution of the laser created plasma was followed using a Schlerin diagnostic



Only light which is deflected will make it through.

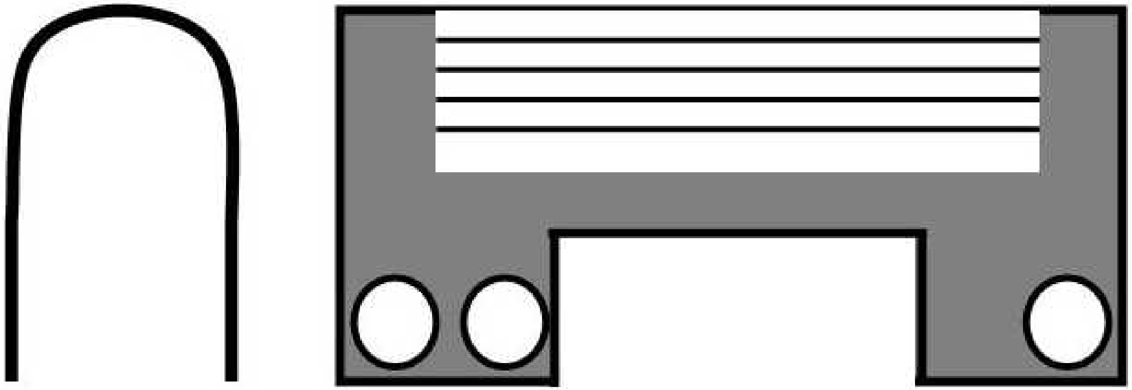
1000 J shot in nitrogen gas after 500 ns



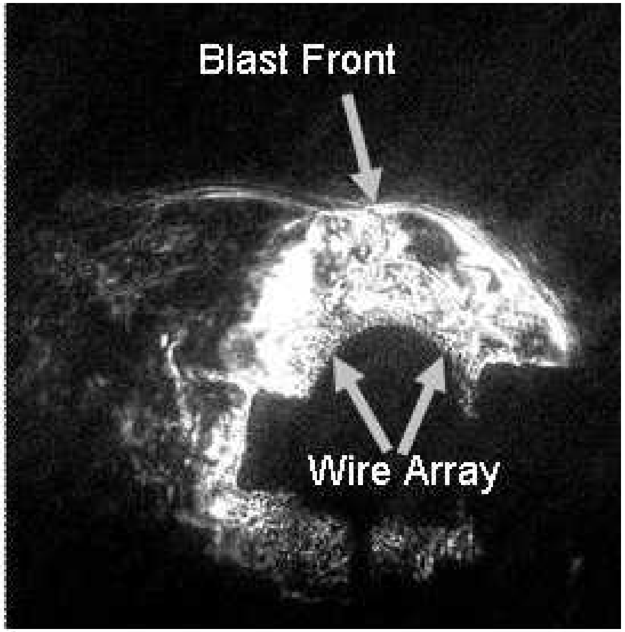
Blast Front

Laser in

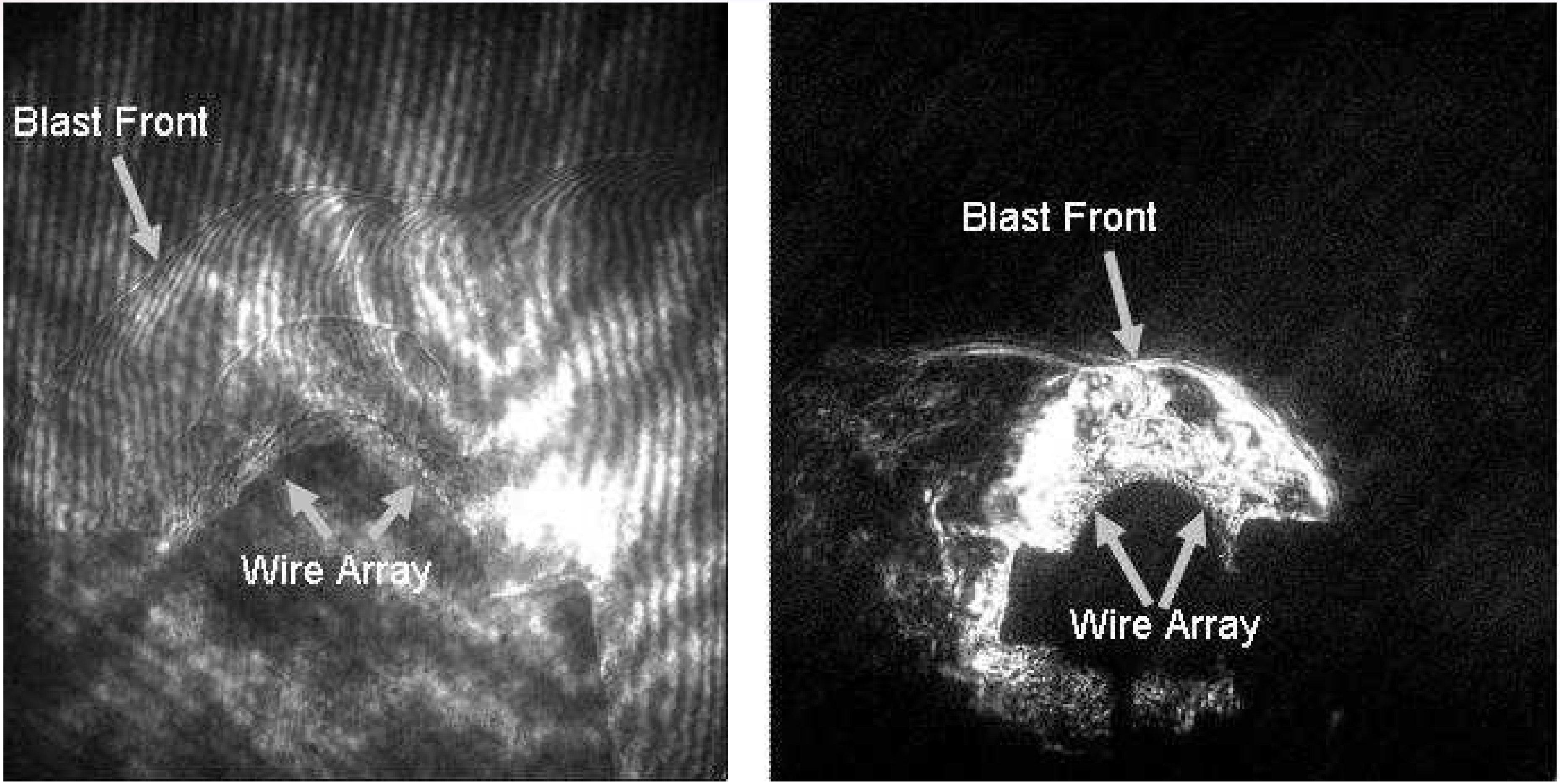
A half-cylinder wire array was used to induce perturbations.



Wire Spacing	l number Y_{lm}
2 mm array	30
3 mm array	20
4 mm array	15

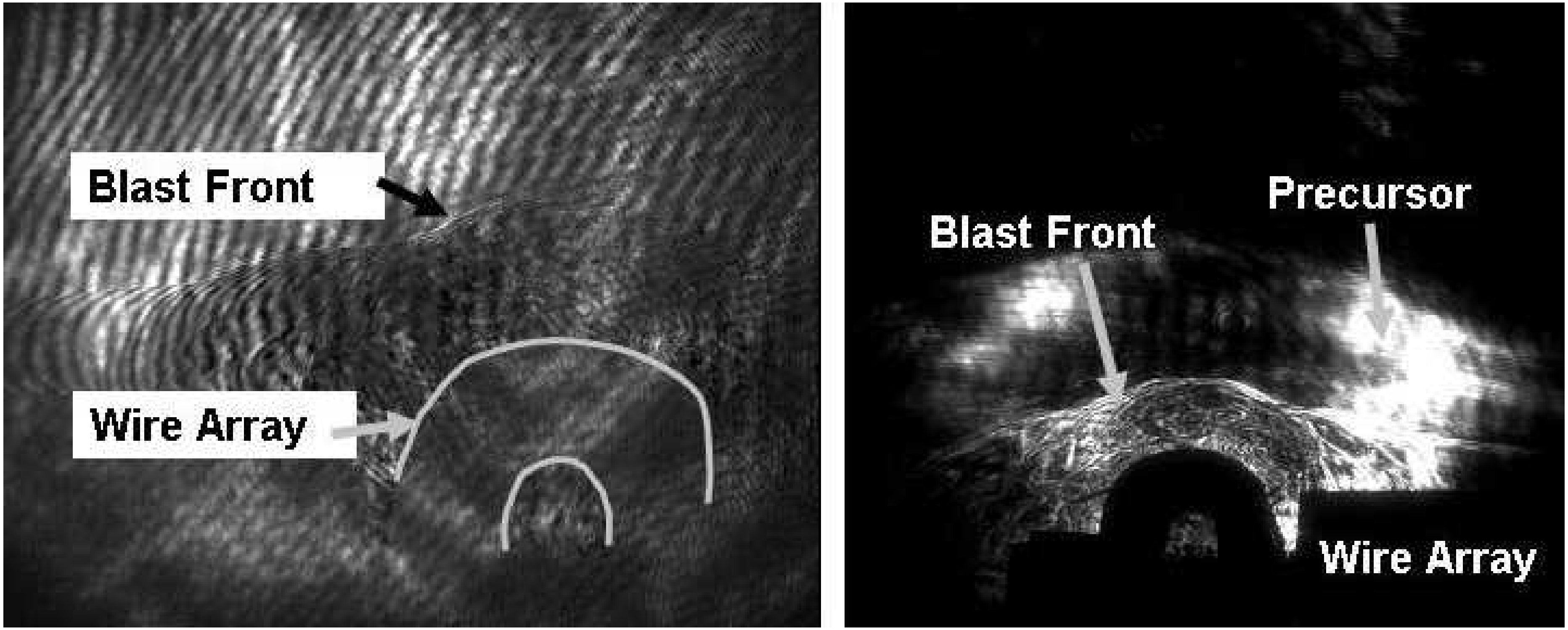


Blast waves would travel past the wire array and induced perturbations could be studied.



1000J shot in helium gas after 300 ns, 4 mm spaced array

We could vary the importance of radiation via differences in the gas type.



1000J shot in a mixed gas after 1400 ns, 4 mm spaced array

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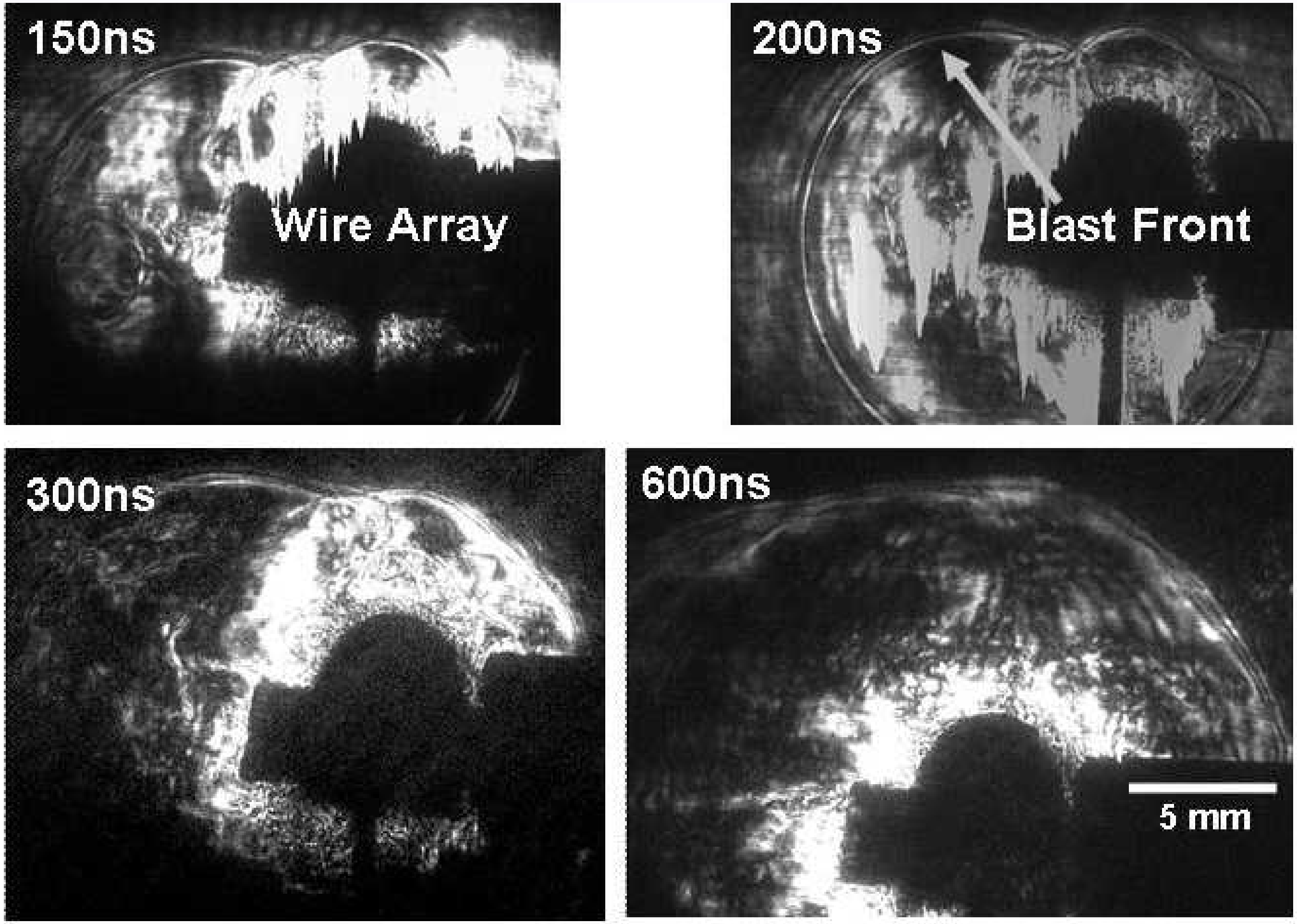
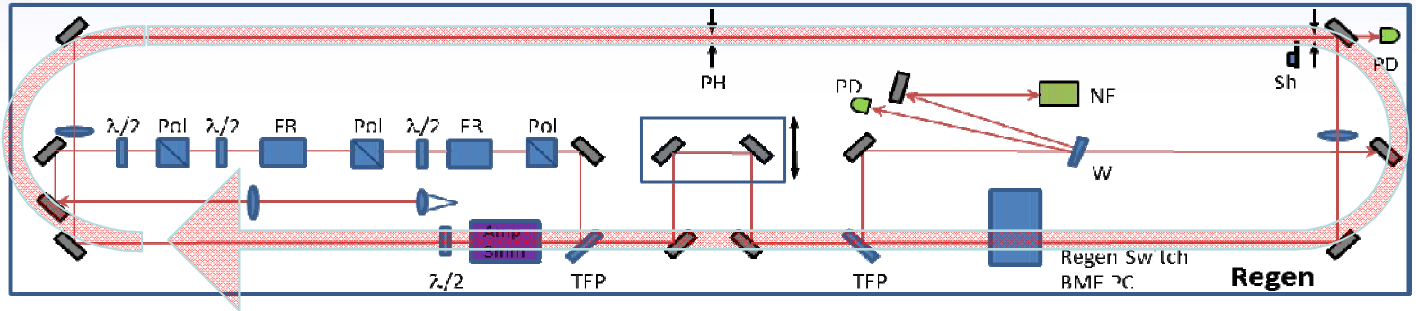
By varying the delay between the main and probe lasers, we could watch perturbation evolution.

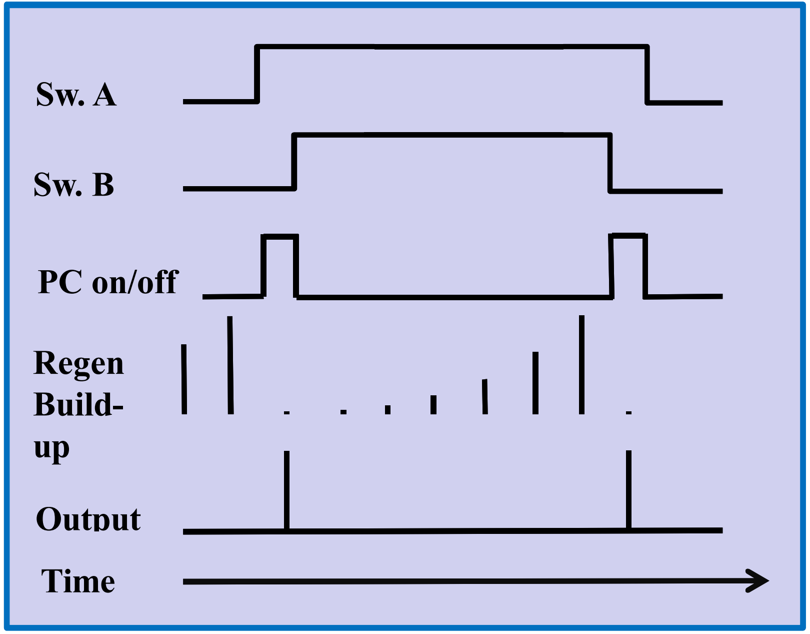


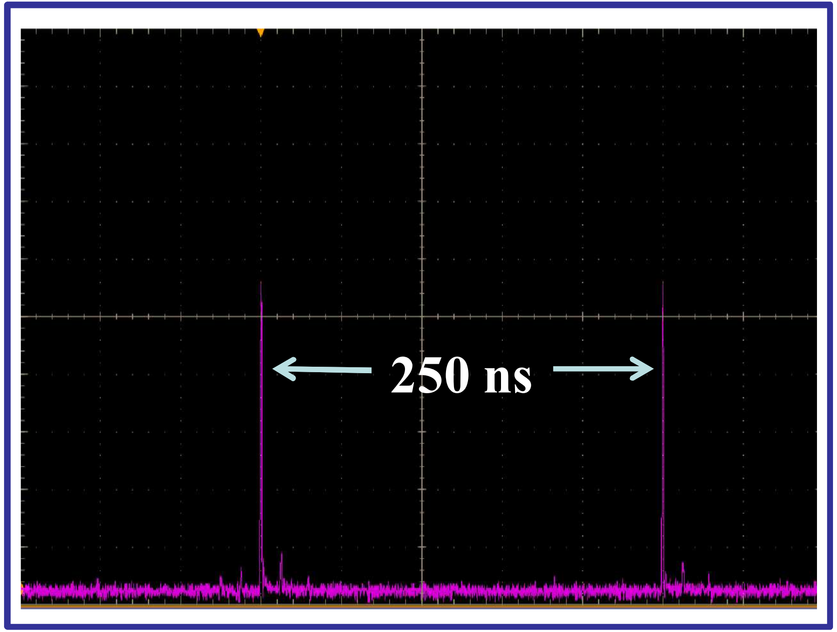
Multi-pulse operation is crucial for increasing our understanding of the blast wave behavior.

12.5ns round trip



- **Utilizes unique burst-mode capability of Pockels cell**
- **Variable pulse separation time is a multiple of cavity round trip time (12.5 ns)**





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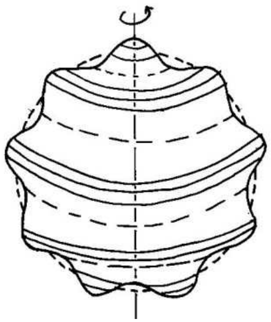
Future plans:

- **Improve the comparison of experimental results to numerical simulation**

  - appropriate perturbation in the flow (parallel wires ? …) - axial symmetry is easier



$R_{pert}(t=0) = R(t=0).[1 + A \times \cos(l\,\theta)]$ for instance …

like in the numerical simulations

Expand $\cos(l\,\theta)$ in eigenmodes: $Y_{l,m=0}(\theta)$

The dispersion relation between the growth rate and the mode is known

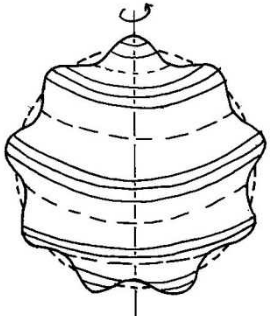
  - VI vs. RTI: modulation of the laser pulse to produce various acceleration profiles
  - theory: derivation of a new dispersion relation due to cooling and to non-isothermality
  - comparisons experiments - theory - numerics (linear, non-linear, γ effect)

- **Utilize new experimental capabilities to further understanding of the blast waves**
  - Multi-frame imaging of an experiment allows better observation of oscillation
  - Spectroscopic observations may improve knowledge of hydrodynamic conditions

Prospects:

- **Experimental adiabatic blast waves in spherical geometry**

  - optically thick gas (adiabatic - no cooling at the front)
  - appropriate perturbation in the flow (parallel wires ? …) - axial symmetry is easier



$R_{pert}(t=0) = R(t=0).[1 + A \times \cos(l\,\theta)]$ for instance …

like in the numerical simulations

Expand $\cos(l\,\theta)$ in eigenmodes: $Y_{l,m=0}(\theta)$

The dispersion relation between the growth rate and the mode is known

  - experimental linear stage: comparisons with analytical results **Overstability ?**
  - experimental non-linear stage: comparisons with numerical simulations **Smoothing ?**
  - VI vs. RTI: modulation od the laser pulse to produce various acceleration profiles

- **Experimental non-adiabatic (cooled) blast waves in spherical geometry**
  - optically thin gas (cooling at the front) - formation of a thin dense shell is expected
  - extension of the Vishniac « thin dense shell » results to $\gamma \neq 1$
  - theory: derivation of a new dispersion relation due to cooling and to non-isothermality
  - comparisons experiments - theory - numerics (linear, non-linear, γ effect)

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