SAND2007-0706C

Dynamics of Large and Small Scale Structures in the Plasma Column of Wire Array Z-pinches

V. V. Ivanov*, V. I. Sotnikov*, G. S. Sarkisov**, T. E. Cowan*, B. Jones***, C. Deeney***, A. L. Astanovitskiy*, P. Laca, A. Haboub*

- University of Nevada, Reno; **- Ktech Corp.; *- Sandia National Laboratories*

Abstract

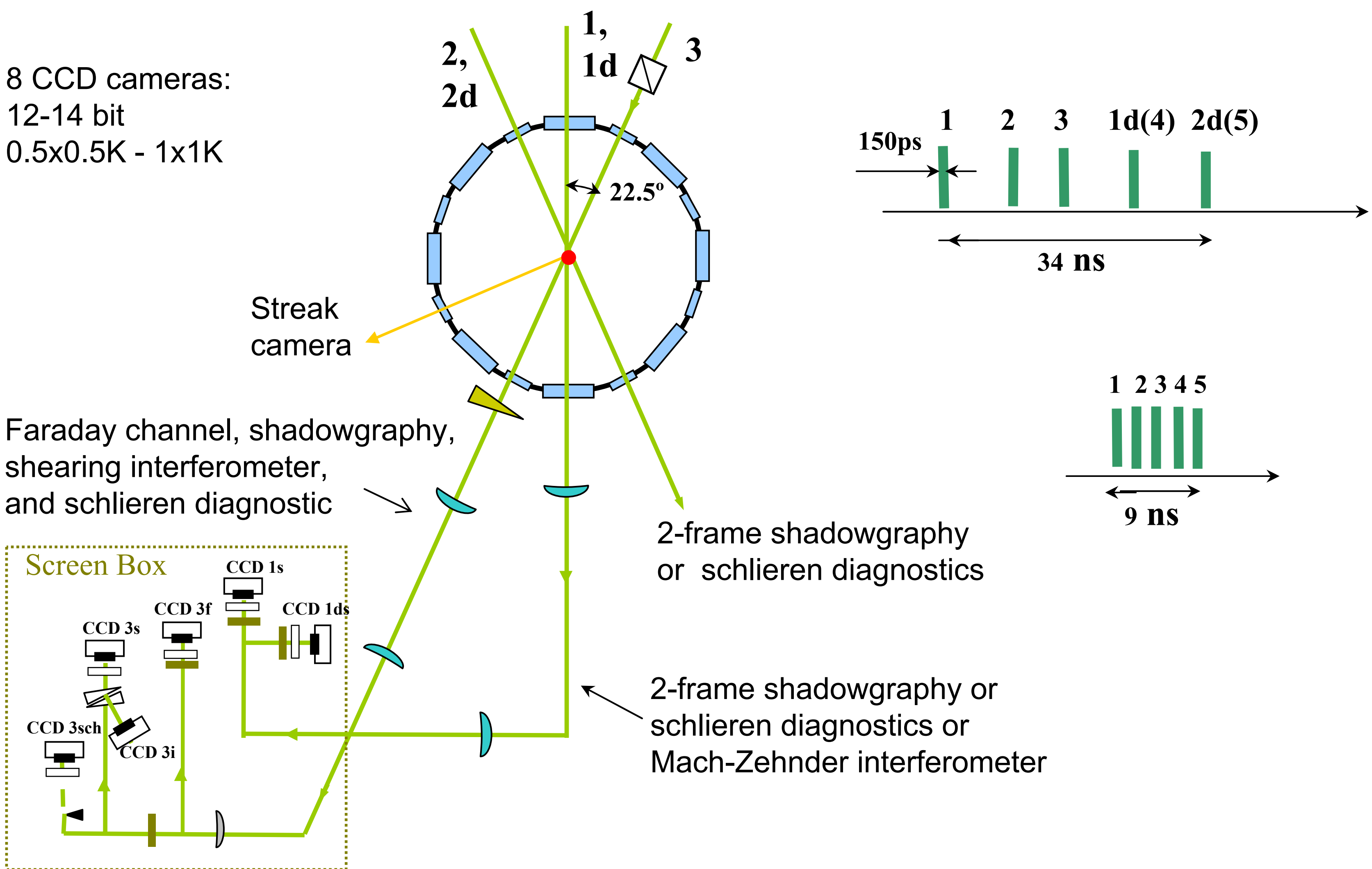
Dynamics of large- and small-scale plasma structures were investigated in the precursor of 1-MA wire array Z-pinches by laser probing diagnostics. It was found that plasma streams from the wires induce density perturbations in the precursor. Small-scale perturbations and large-scale cells arose in the nonlinear stage before the implosion. Spatial and temporal scales of observed structures are in agreement with theoretical investigation for current driven excitation of electromagnetic flute modes.

Work was supported by the DOE/NNSA under UNR grant DE-FC52-01NV14050 Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US DOE under Contract DE-AC04-94AL85000

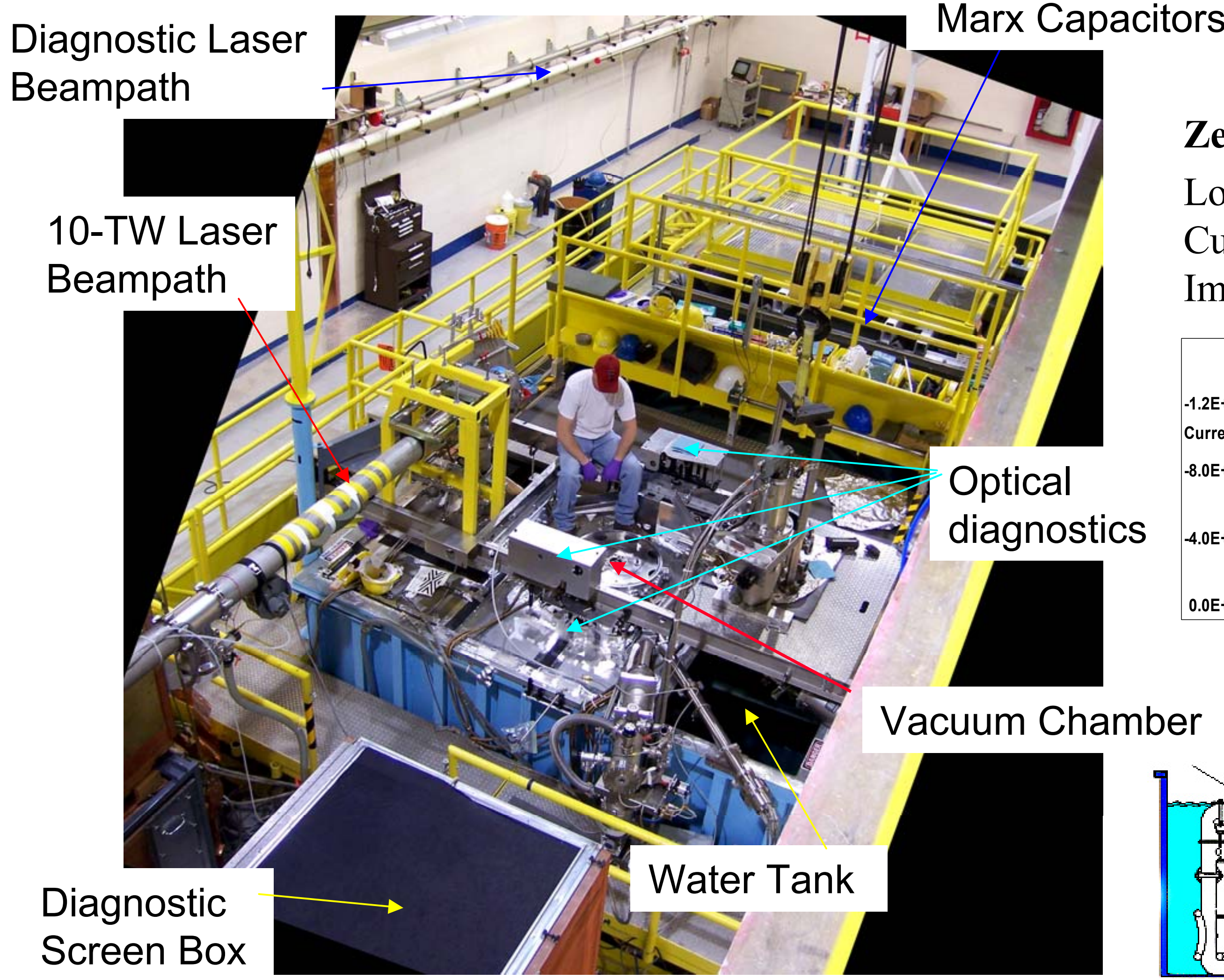
Sandia National Laboratories

Laser Diagnostics on the Vacuum Chamber of Zebra

8 CCD cameras:
12-14 bit
0.5x0.5K - 1x1K



1-MA Zebra Generator at the NTF

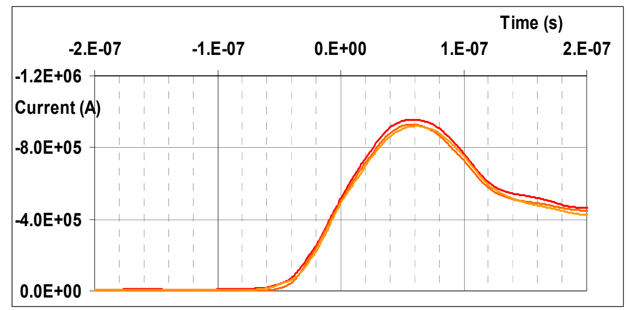


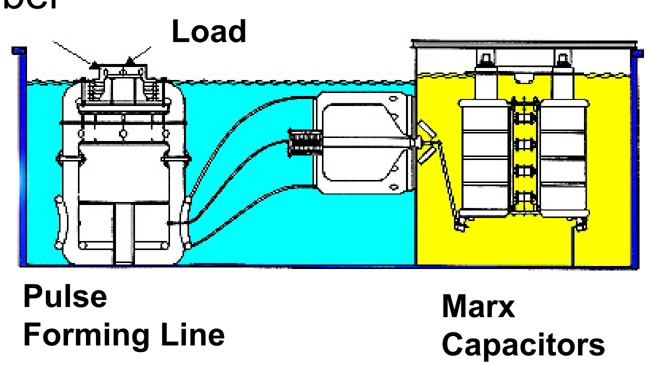
Zebra operation:

Load current 1.2 MA

Current rise time 80 ns (10%-90%)

Impedance 1.9Ω





Motivation to Study Plasma Turbulence in Z-pinches

- The observed x-ray yield of wire array Z-pinches cannot always be explained by kinetic energy and Spitzer resistive heating;

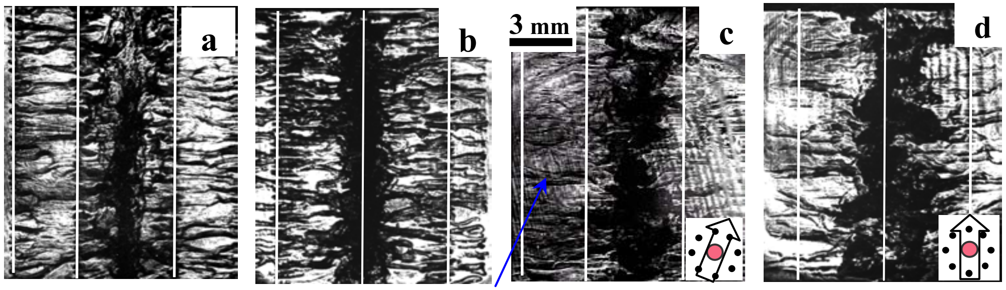
- Plasma turbulence can enhance energy deposition to the Z-pinch;

- Dynamics of plasma turbulence has not been investigated experimentally in wire array Z-pinches.

Different regimes of Al wire array implosion were observed at Zebra

Plasma column of the precursor collapses before the x-ray pulse

Al 8 x 15 µm wire array

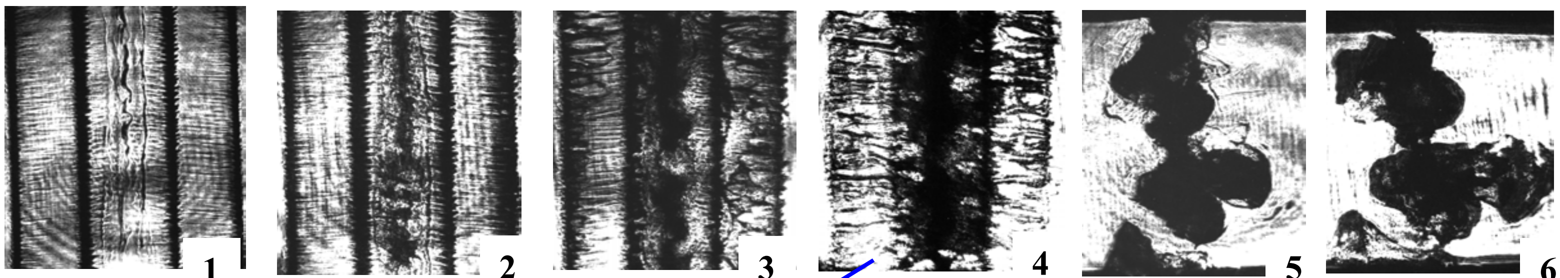


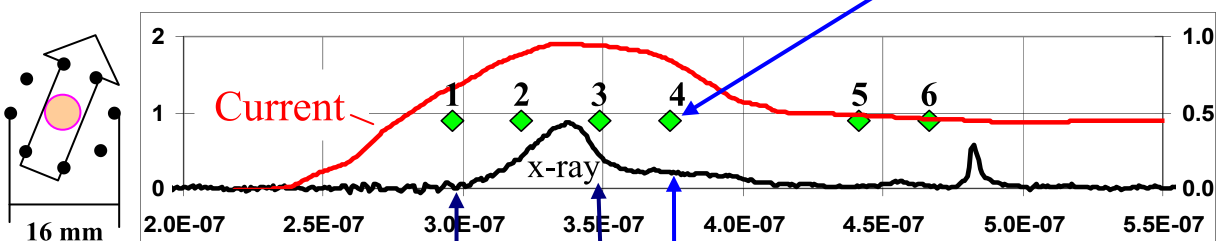
MHD instabilities arise in the pinch after the maximum of the x-ray pulse

"Dense pinch" implosion is typical in Al 16x10 µm and 8x15 µm wire arrays

Implosion in "overmassed" 16x15 µm and 8x20 µm Al loads

Three pairs of two-frame shadowgrams from shots 503(1, 2), 525(3, 4), 523(5, 6)





The X-ray yield is 2-3 times smaller than in the "dense pinch" regime

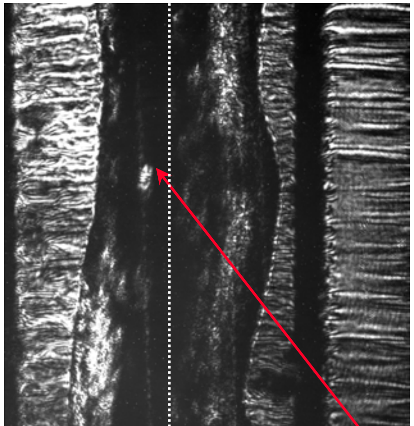
The plasma column exists during the main x-ray pulse

"Cold" implosion does not produce strong x-ray radiation

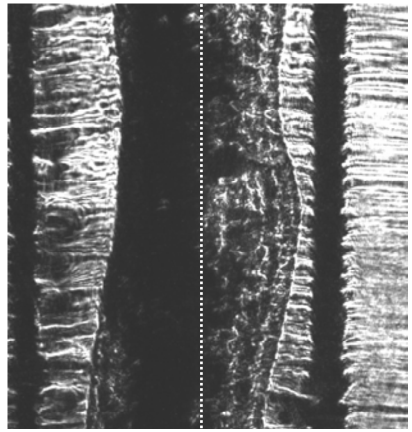
V.V. Ivanov et al., Phys. Plasmas 13, 012704 (2006).

The Faraday effect shows current in the precursor of Al arrays

Al 16x15µm wire array



α_0 = -5°

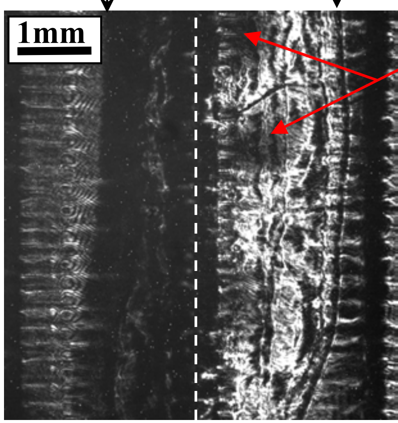


Faraday channel

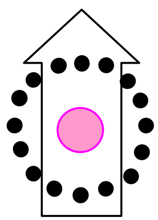
Shadowgram

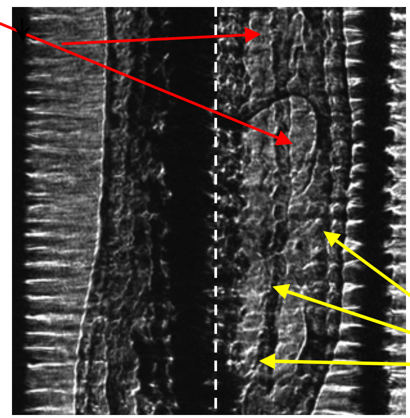
Magnetic bubbles

Precursor



α_0 = +5°





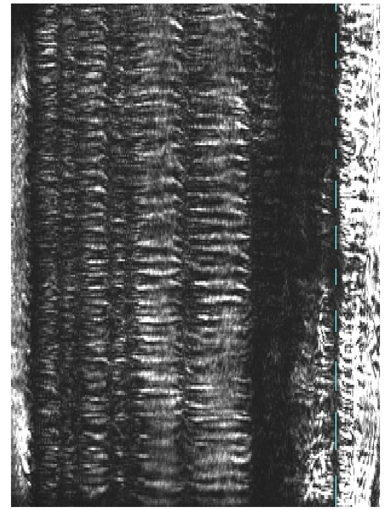
Faraday channel

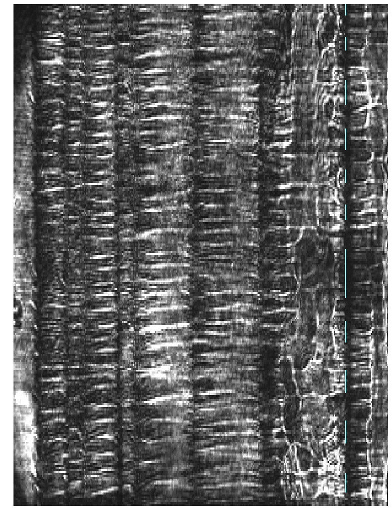
Shadowgram

Stripes of cells

Al 24x10 µm wire array

Precursor





Faraday channel

Shadowgram

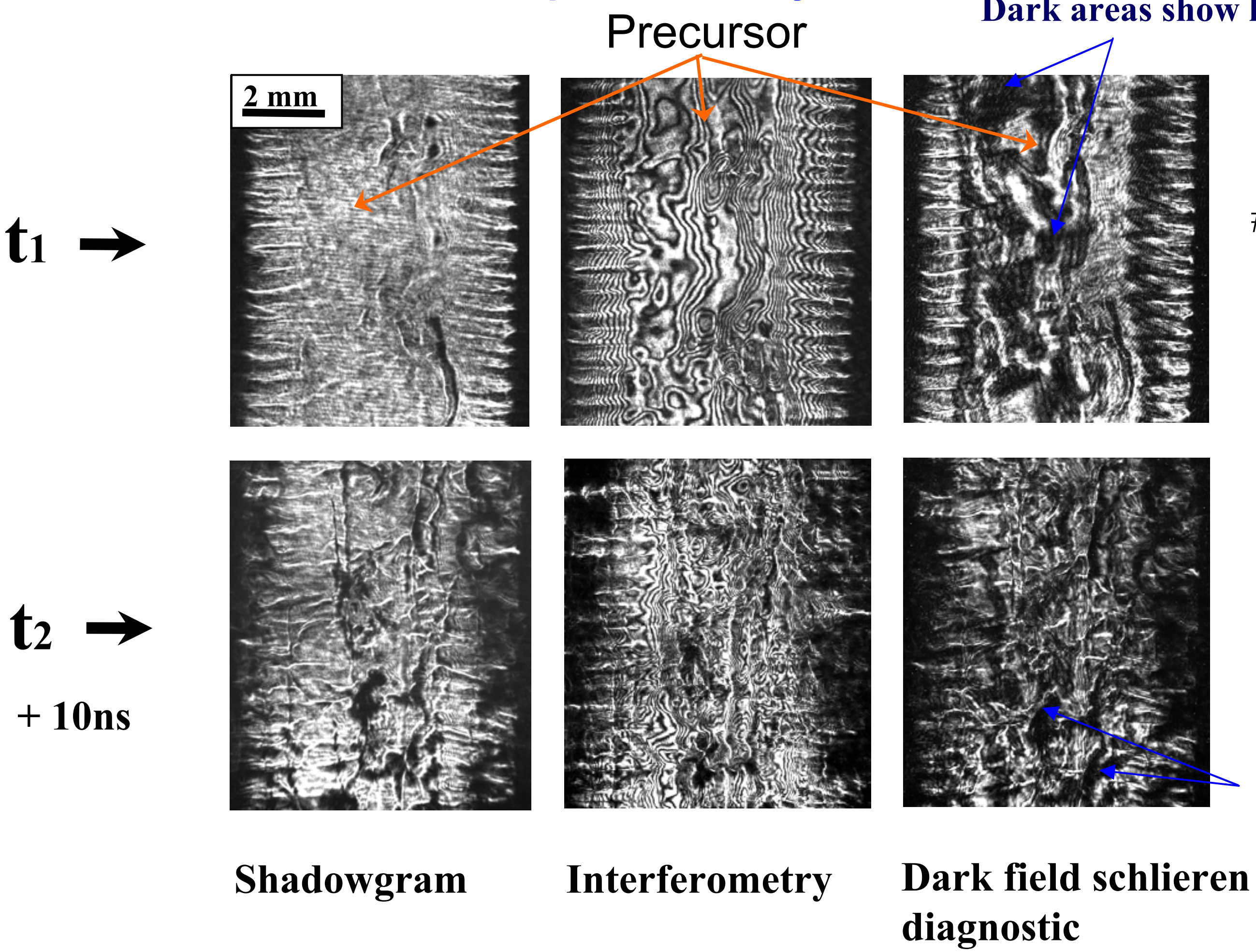
I = 0.1-0.2 MA

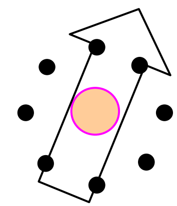
Current can initiate plasma instability in the precursor plasma

*-V. Ivanov et al., "Investigation of Magnetic Fields in 1-MA Wire Arrays and X-pinches", IEEE TPS 34, 2247 (2006)

Perturbation in the Plasma in the Precursor

Al 8 x 15 μm wire arrays





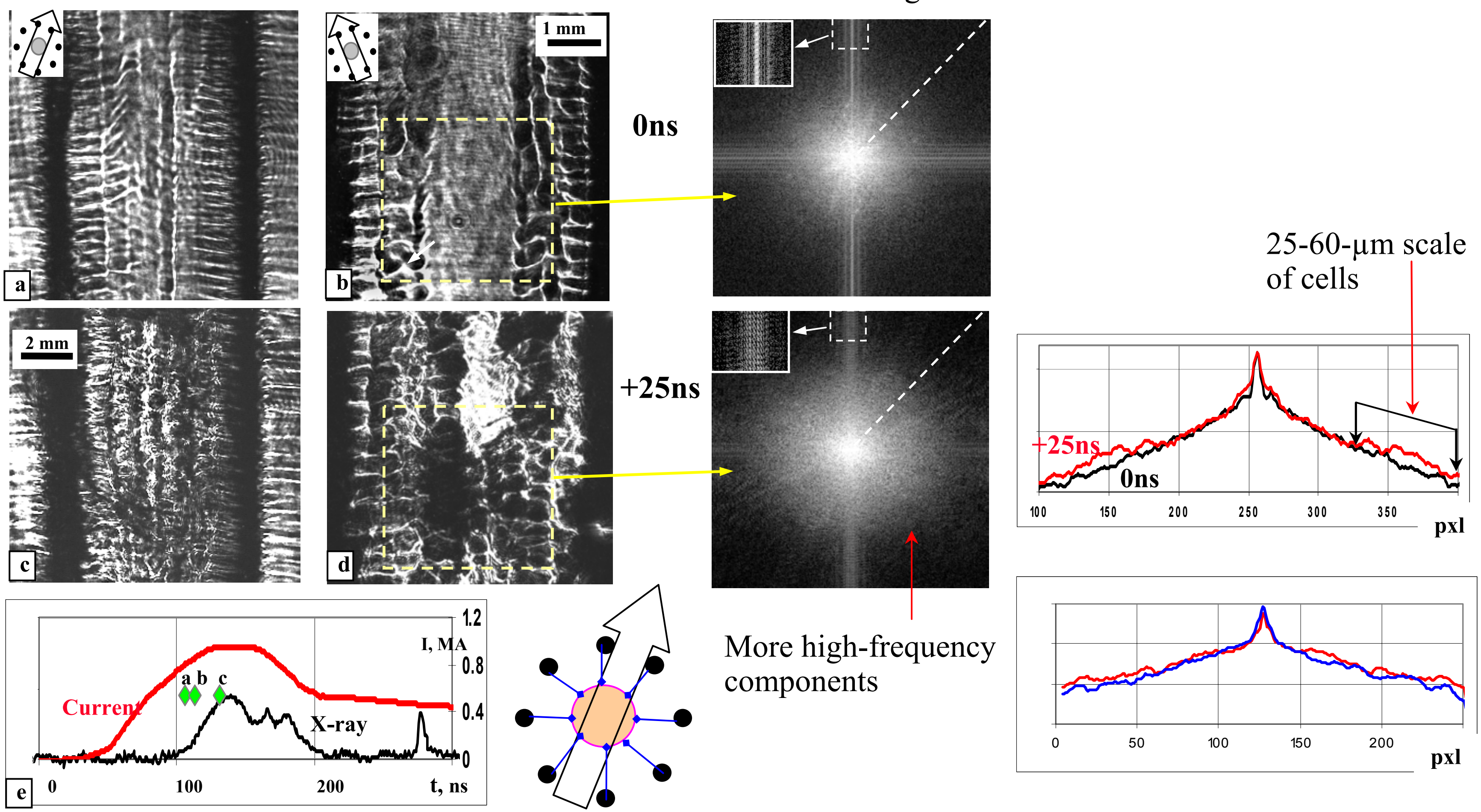
* - B. Jones at the NTF

Dynamics of Plasma Structures in the Precursor

Al 8 x 20µm wire arrays

a, b, and c - #500; d – #505.

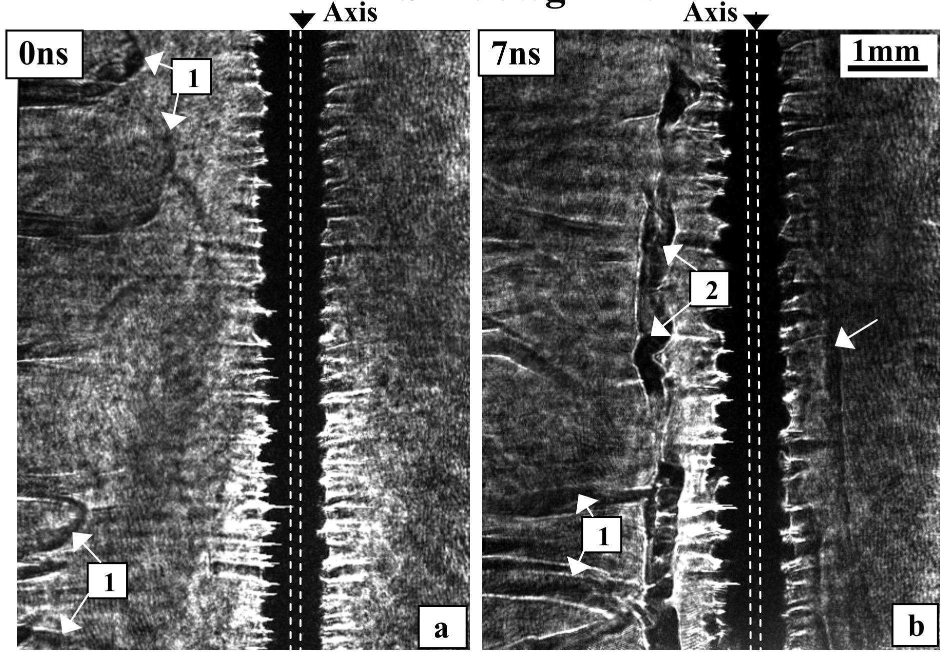
Fourier images



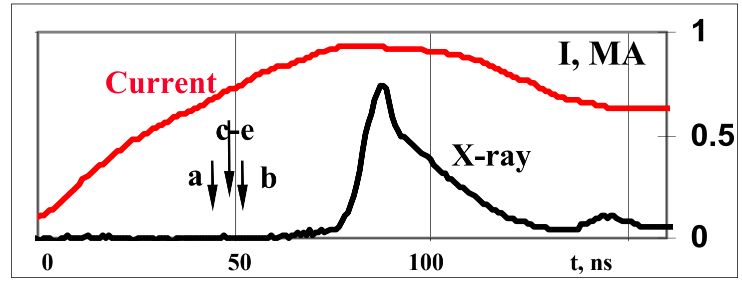
***-V.V. Ivanov et al., "Experimental study of the dynamics of large- and small-scale structures in the plasma column of wire array Z-pinches ", submitted to Phys. Plasmas**

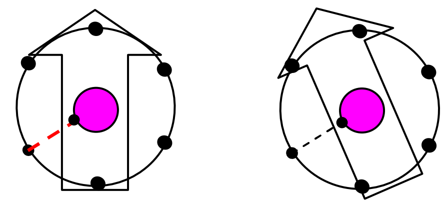
Formation of Strips of Cells on the Precursor Surface

Shadowgrams



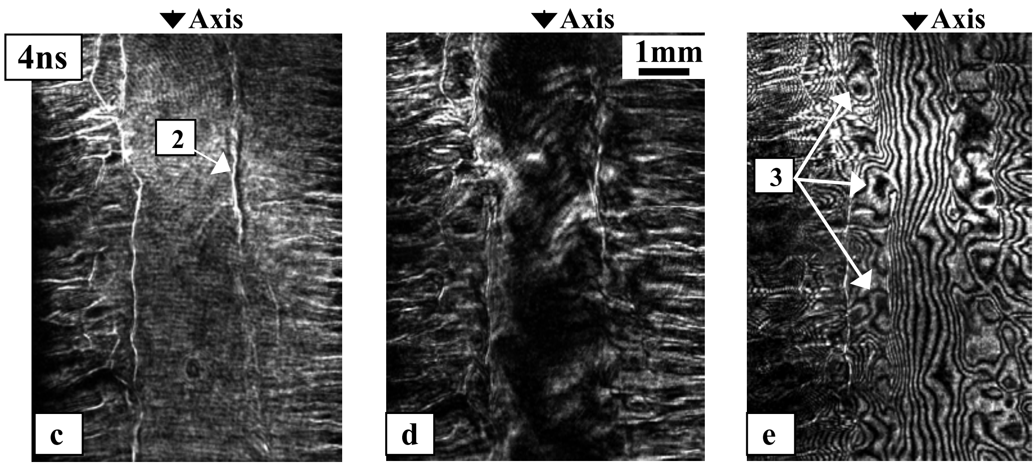
#643. Al 6 wires,
5x18 µm + 1x10 µm





Frames a, b

Frames c -e



Shadowgram

Schlieren

Interferometry

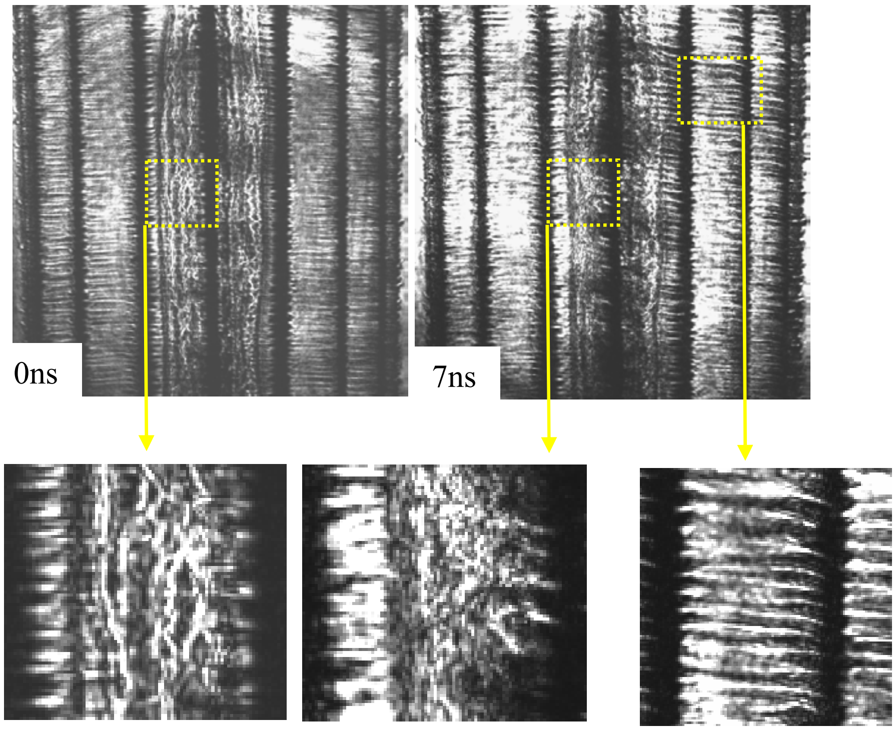
1 - plasma bubbles moving from the 10-µm wire to the center.

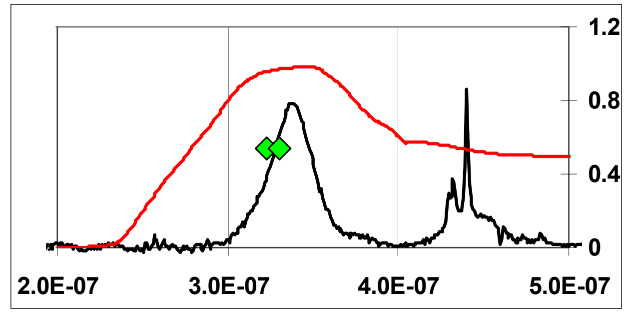
2 - traces of ablation jets on the surface of the plasma column.

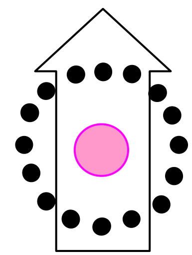
4 - localized density perturbations.

Plasma perturbations cascade to smaller scales

Shadowgrams





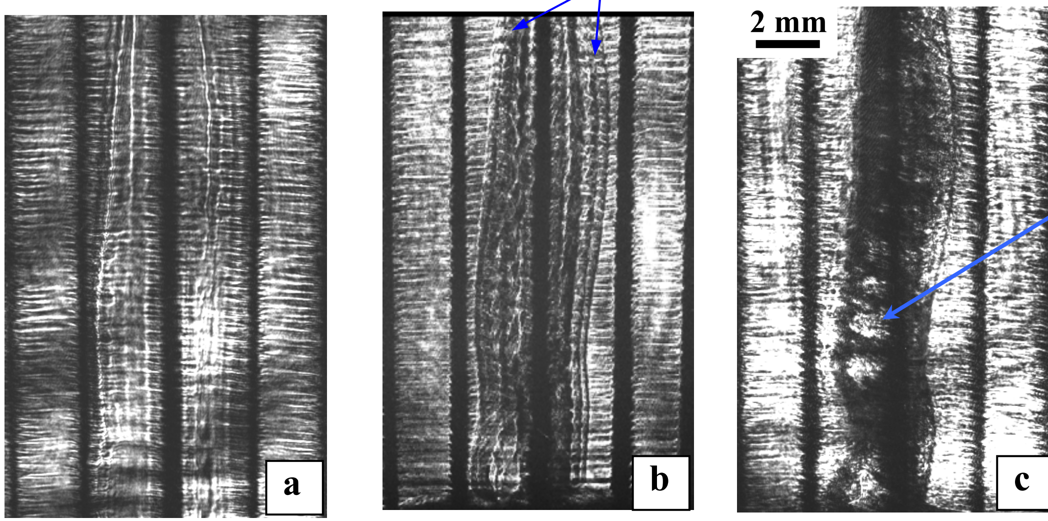


Al 16x15 µm wire array

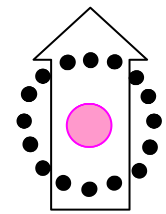
Large-scale structures (in addition to small scale) arise in the nonlinear stage

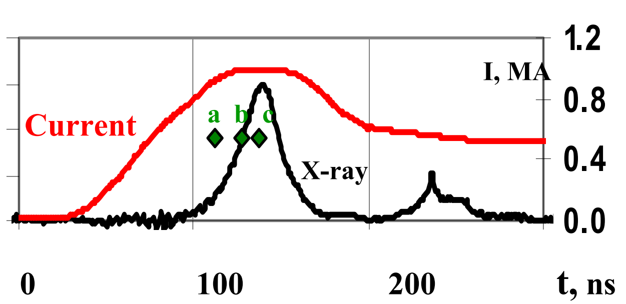
Al 16 x 15 μm wire arrays

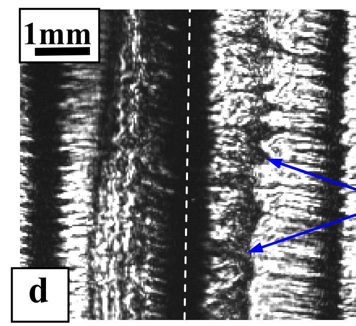
Imprints from wires



Convective cells?







#501

Bubbles arise in the chain of cells

Evolution of Cells and Perturbations in the Plasma Column

1. Plasma is homogeneous in the beginning of the precursor phase.

2. Streams from the wires imprint the surface of the precursor and seed instabilities. Imprints produce strips of cells with the same size scale as the period of the streams.

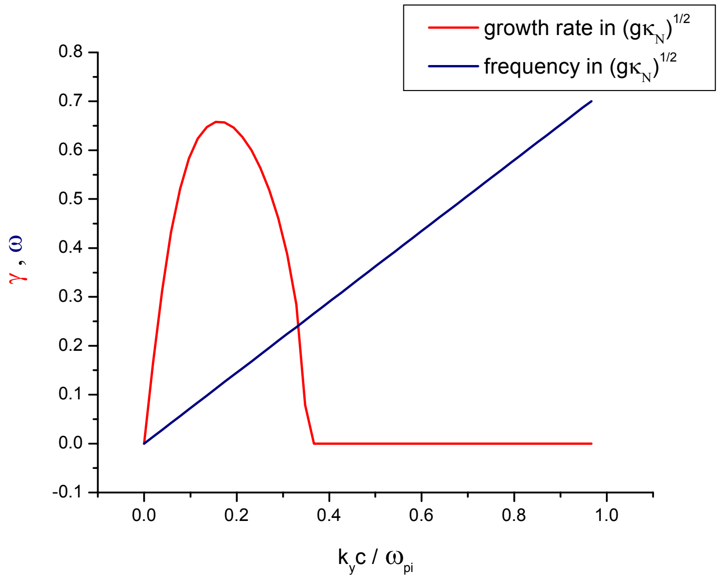
3. Small-scale perturbations and large-scale cells arise in the nonlinear stage.

These turbulent processes may impact energy deposition in the z-pinch

An electromagnetic flute mode theory was developed to investigate observed plasma structures in high beta precursor plasma*

Two-fluid hydrodynamic equations, with inclusion of gyroviscosity, provide positive solution for the growth rate of instability

Typical plasma parameters in the precursor:



$$T_i = 40 \text{ eV} \quad n_0 = 3\times 10^{19}\ cm^{-3} \quad B_0 = 0.3\ MG$$

$\beta_i \sim 0.5–1$

$$\frac{\omega_{pAl}}{c} = 4\times 10^{2}\ cm^{-1} \qquad \frac{kc}{\omega_{pAl}} \sim 0.2 \qquad \lambda \sim 0.8 \text{ mm}$$

The growth rate of instability developing from equilibrium is: $\gamma \sim 3{\cdot}10^{7}\ s^{-1}$

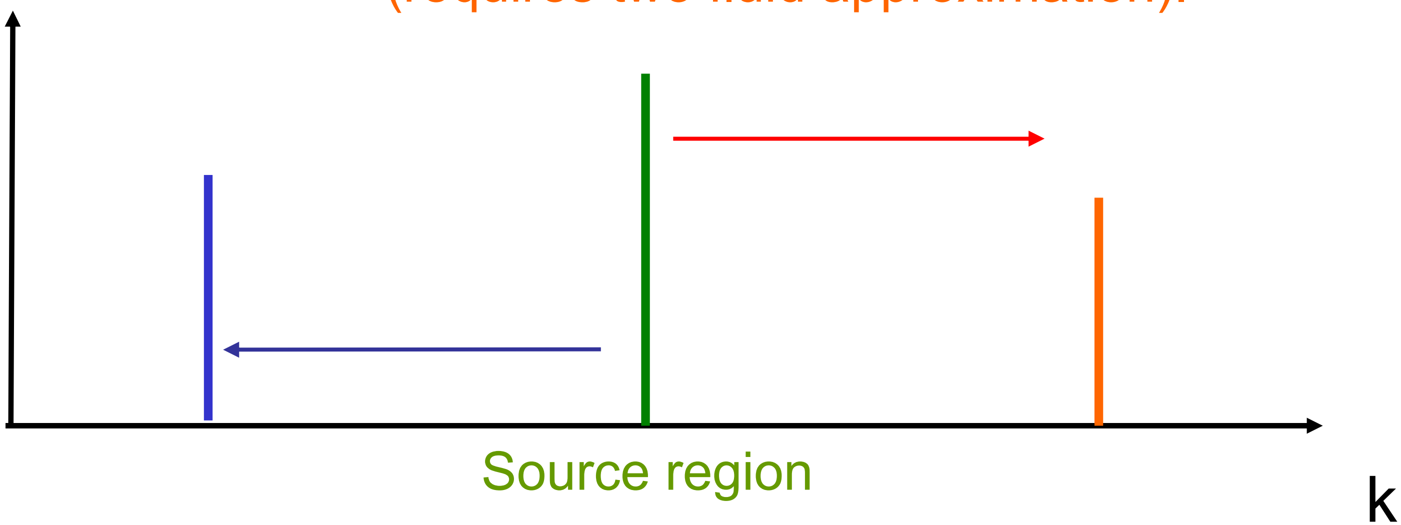
Growth rate and scale size of flute modes in high beta plasma are consistent with experimental data

*** - V.I. Sotnikov et al., "Investigation of electromagnetic flute-mode instability in high-beta z-pinch plasma", IEEE TPS 34, 2239 (2006)**

Nonlinear wave cascades

EM flute theory predicts nonlinear cascades to larger and smaller wave numbers k

Wave energy cascades to small wavelengths due to E $\times$ B nonlinearity and associated ion heating (requires two fluid approximation).



Wave energy cascades to larger wavelengths (similar to MHD inverse cascades) and excitation of large scale structures due to polarization drift nonlinearity (provides enhanced transport across the magnetic field)

Plasma Instabilities in the Precursor

Low-hybrid oscillations: $\lambda_{LH} = \dfrac{2 \cdot \pi \cdot V_{Te}}{\omega_{ce}}$

If T_e=40 eV, B=0.2 MG, $V_{Te} = \sqrt{\dfrac{k \cdot T_e}{m_e}} \sim 2.6 \cdot 10^8 \dfrac{cm}{s}$, $\omega_{ce} = \dfrac{e \cdot B}{m_e \cdot c} \sim 1.7 \cdot 10^{13}$

$\lambda_{LH} \sim 5\ \mu m$

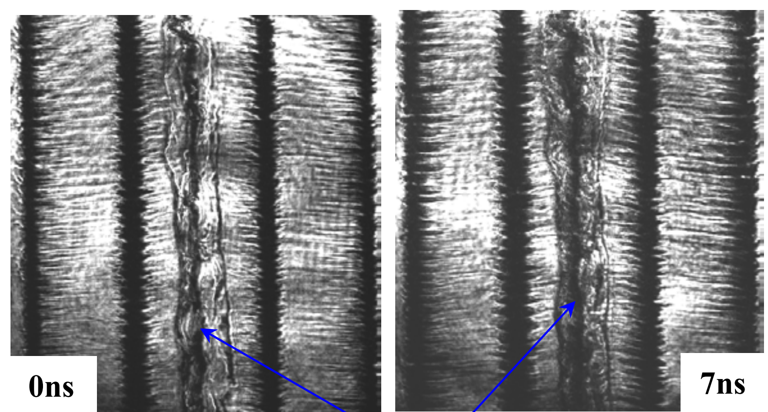
MHD instabilities:

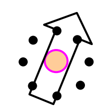
$$\lambda_{MHD} \geq \frac{2 \cdot \pi \cdot c}{\omega_{pi}} \sim 1 mm,$$

$$\omega_{pi} = \sqrt{\frac{4 \cdot \pi \cdot N_e \cdot e^2 \cdot Z^2}{Mi}} \sim 2 \cdot 10^{12}$$

$$\gamma_{MHD} = V_A \sqrt{\frac{k}{a}}$$

Shot 511. Al 8x20 μm





Conclusions

- Dynamics of plasma turbulence was investigated in the precursor of wire arrays in the first time. Magnetic fields indicate current in the precursor. Observed structures and cells can be produced by the current-driven flute mode instability.
- Streams from wires imprint the precursor in the early stage. Later cells occupy the total area of the plasma column.
- Small-scale and large-scale cells arise in the nonlinear stage. Magnetic bubbles were observed in this phase.
- Spatial and temporal scales of observed structures are in agreement with theoretical predictions for current driven excitation of electromagnetic flute modes, based on a two-fluid model.