Beam Physics in X-Ray Radiography Facilities

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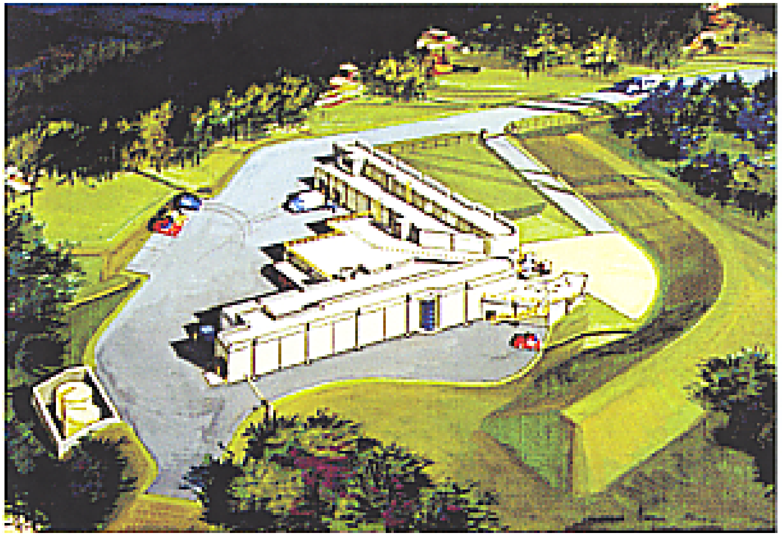
Beam Research Program
Lawrence Livermore National Lab

NNSA

Flash x-ray radiography for hydrodynamics testing needs high resolution and high intensity x-ray

- Ideal facilities for radiography would provide
  - *high-resolution*
  - *multiple-views simultaneously*
  - *multiple-times*
    - The first U. S. facility: DARHT
      - ✓ *1st axis: single pulse*
      - ✓ *2nd axis: 4 pulses in 2 μs*
- Nominal beam parameters at the x-ray converter targets
  - *20 MeV*
  - *2 kA, 20 - 100 ns*
  - *1500 mm-mr*
  - *Time integrated spot ≤ 2.1 mm (diameter; 50% MTF)*



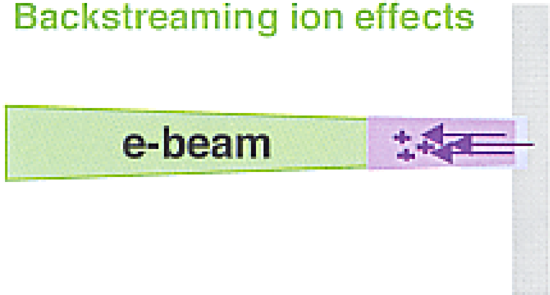
Artist's rendition of DARHT

Beam-target interactions can cause spot size disruption

Single pulse system:

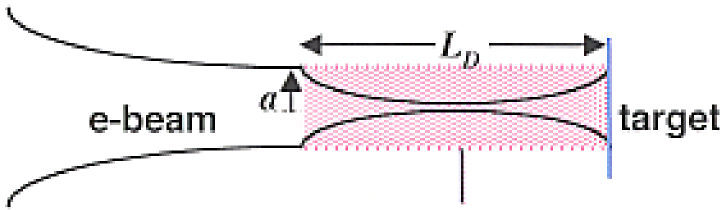
plasma layer generated from desorption of surface contaminants or ionized target material

Backstreaming ion effects



Ion/plasma disruption length

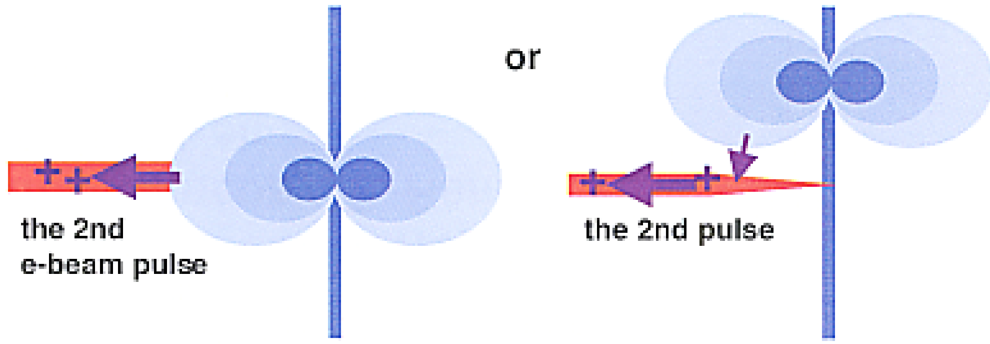
$$L_D \approx a\sqrt{\frac{\pi\gamma\beta^2 I_o}{f I}}$$



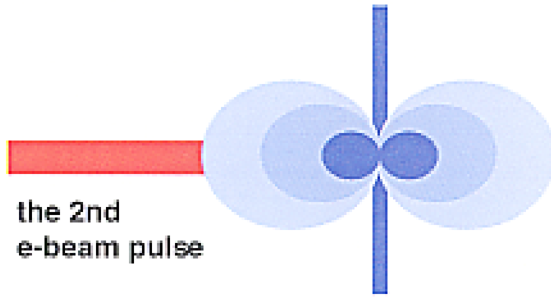
Multiple pulses system:

plasma plume generated by preceding e-beam pulses

Backstreaming ion effects



Beam-plasma interactions



Large efforts have been devoted to beam-target interaction physics since 1997

- U. S.
  - LANL

    H. Davis, T. Kwan, D. Moir, Ross Olson
  - LLNL

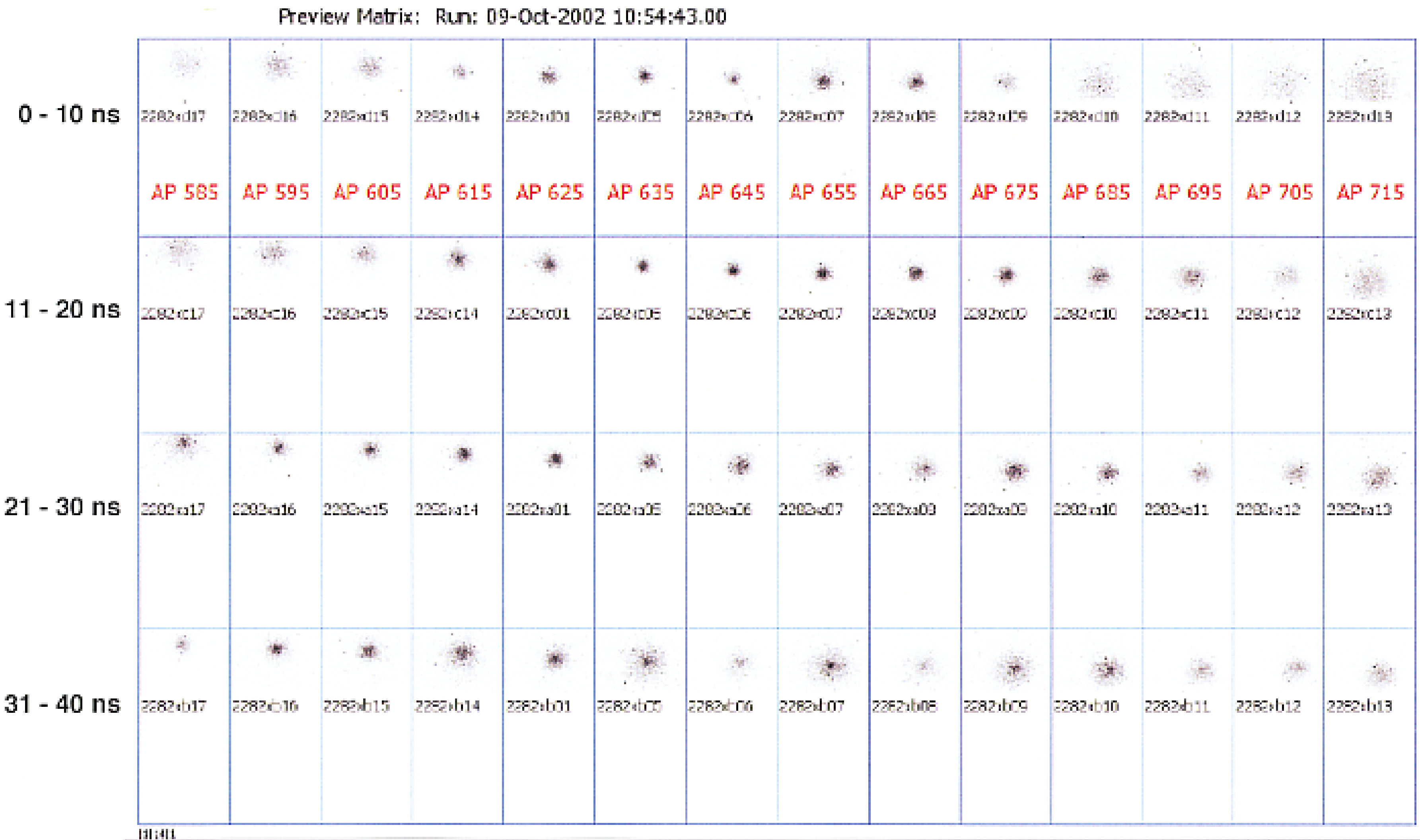
    P. Bergstrom, G. Caporaso, F. Chambers, Y.-J. Chen, S. Falabella, F. Goldin, G. Guethlein, D. Ho, T. Houck, J. McCarrick, R. Neurath, P. Pincosy, P. Rambo, R. Richardson, S. Sampayan, J. Weir
  - MRC

    B. Oliver, T. Hughes, D. Welch
- France
  - AIRIX

    E. Merle, C. Vermare

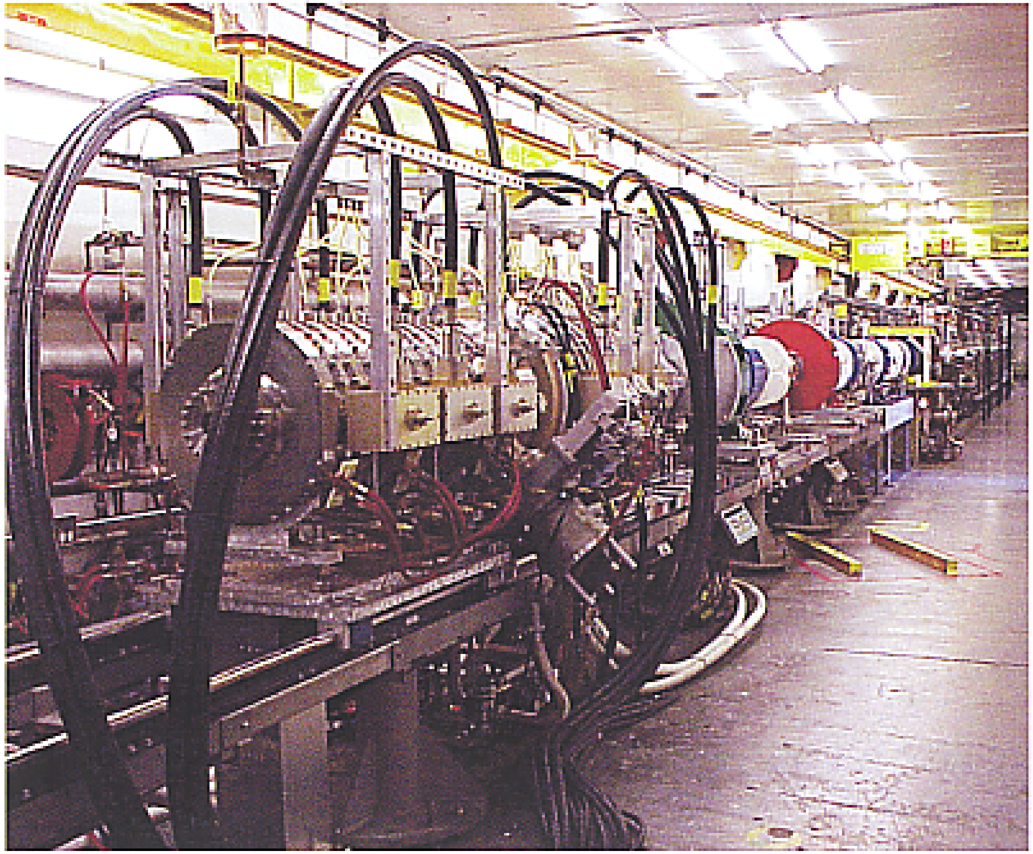
Contents

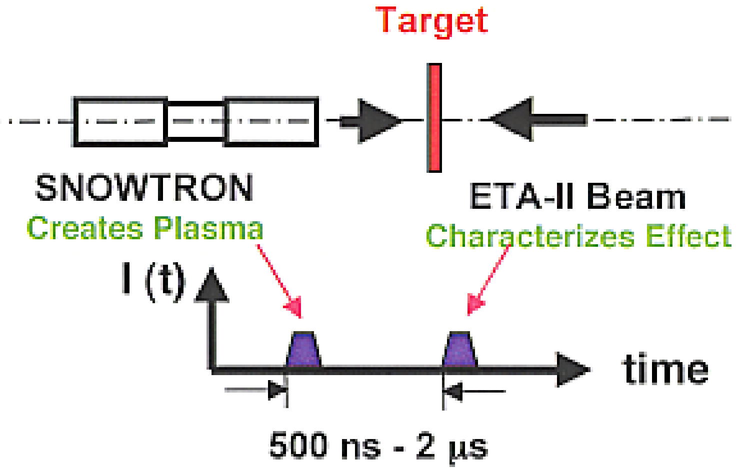
X-ray images of the 6-MeV, 2-kA ETA-II beam hitting a 6 mil Ta foil



Ion Creation, Ion Species and Emission Rate

The multi-pulsing, high x-ray dose converter development activities utilizes ETA-II and Snowtron facilities for target testing





ETA-II double-pulses experiments study:

- Ion emission rate
- Gas desorption threshold temperature
- Foil barrier scheme
- Surface cleaning with e-beam & laser

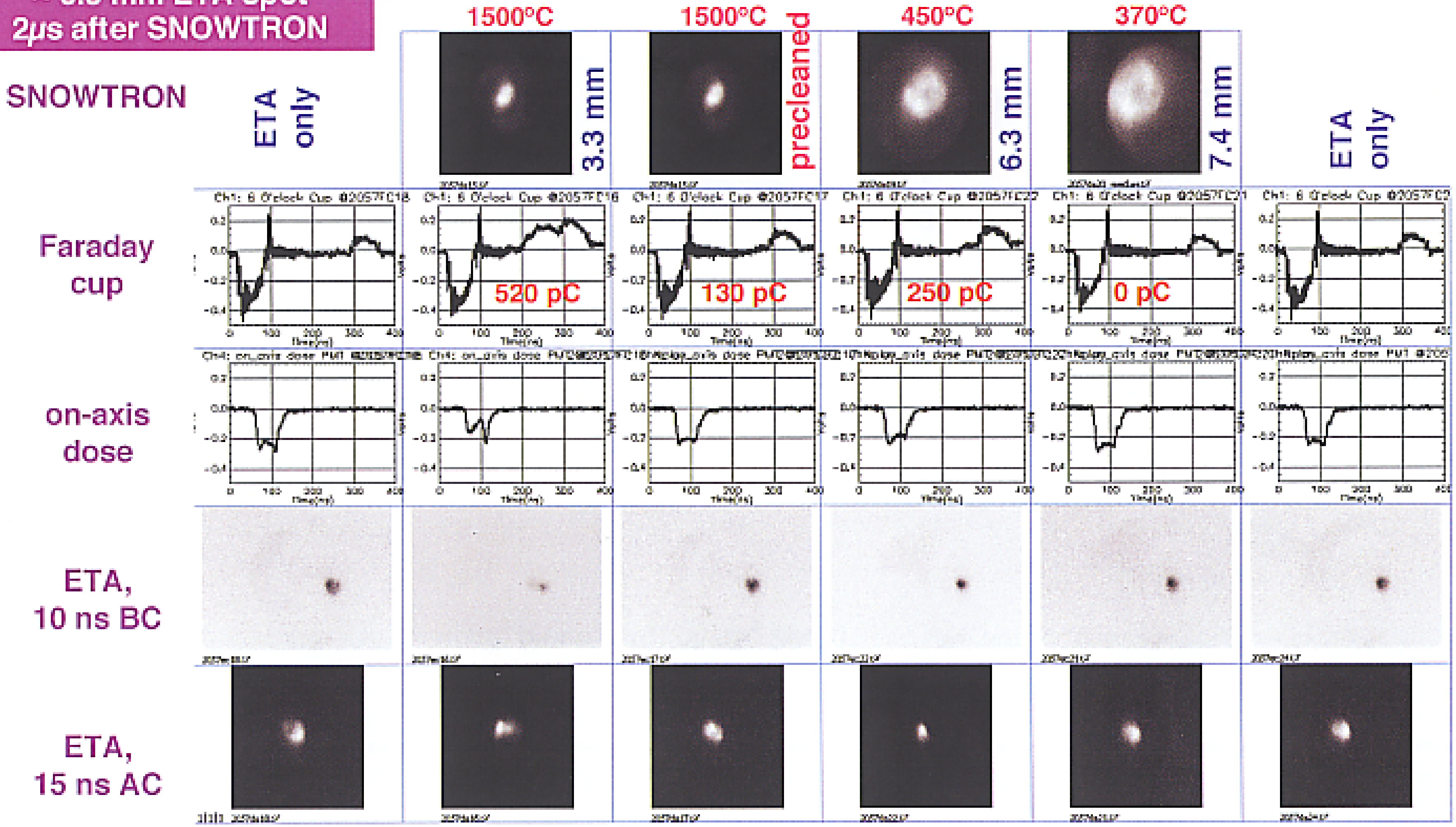
Target experiments on ETA-II with / without a laser study:

- Ion emission rate
- Foil barrier scheme

Spot sizes and x-ray forward doses were highly correlated with ion signals detected with Faraday cup and target temperature

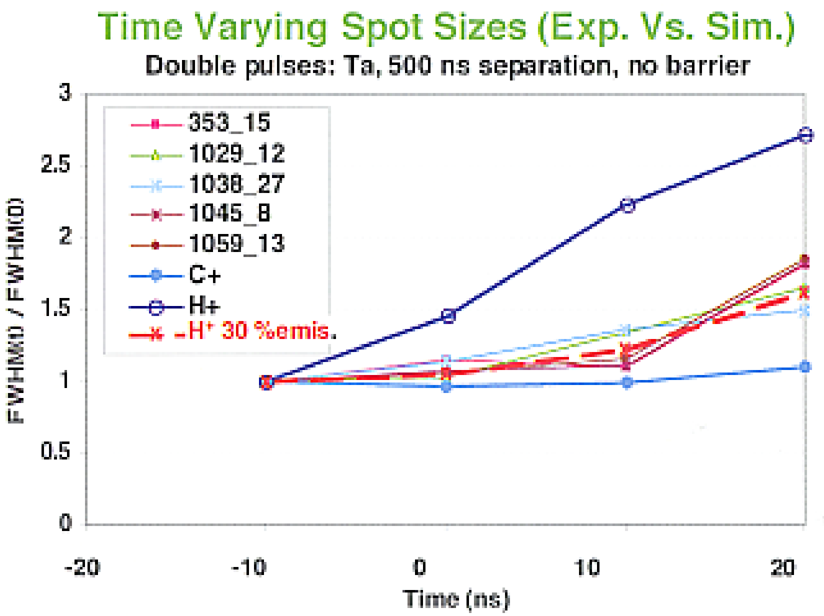
Double pulses on graphite
~ 3.3 mm ETA spot
2μs after SNOWTRON

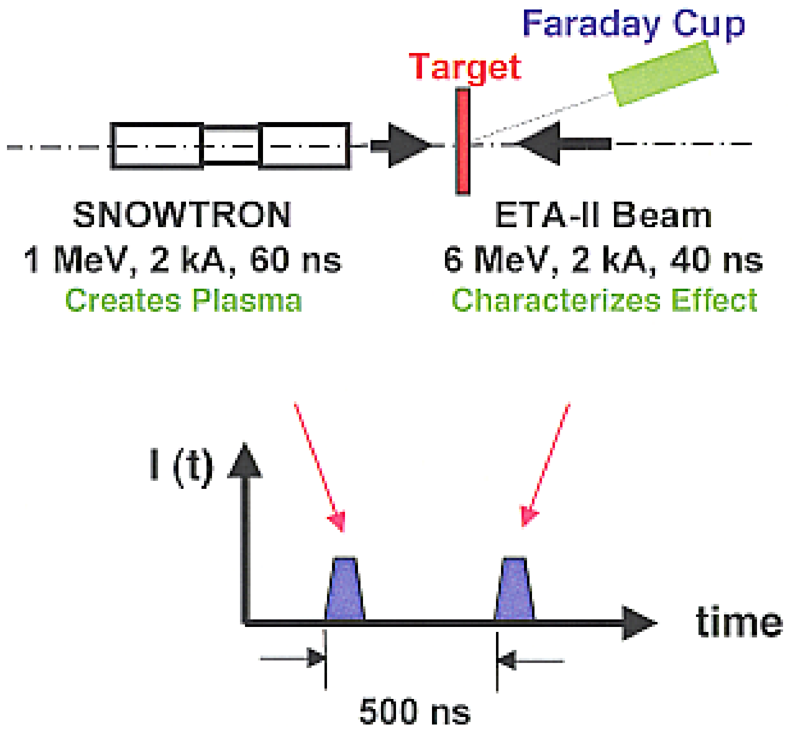
G. Guethlein, et. al., 2002



PIC simulations suggest the ETA-II double pulses experiment's backstreaming H^+ emission rate to be ~ 30 % of the space-charge limited emission rate

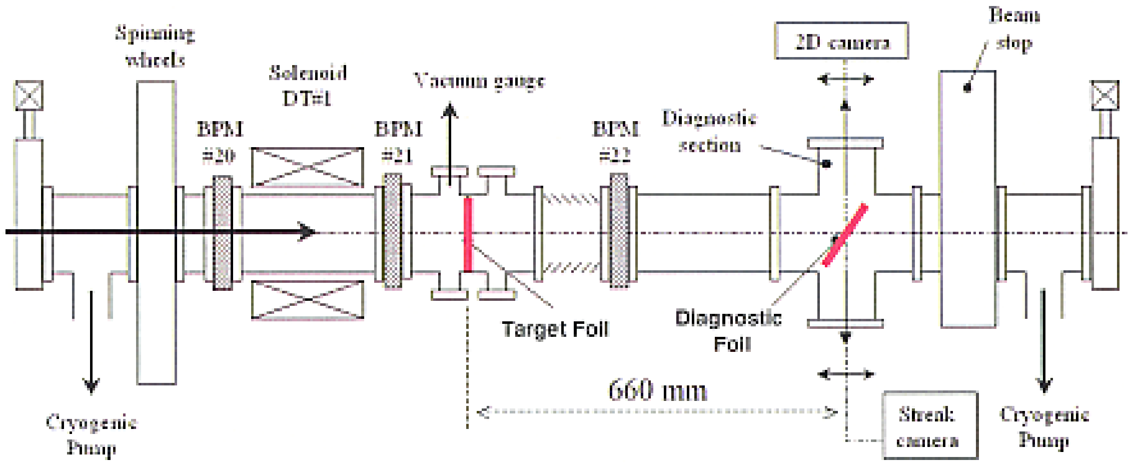
(G. Guethlein, et. al., 2002)





Backstreaming Ion effects have also been investigated with the double-foil experiments

LANL/DARHT-I set up
(H. Davis, et. al., to be published by *Physics of Plasma*)



Foil material

Material	Thickness (μm)
Graphite	66
Aluminium	(a) 7.6 (b)30
Titanium	12.7
Steel	3.8
Molybdenum	12.7
Tantalum	1.5
Gold	1.5

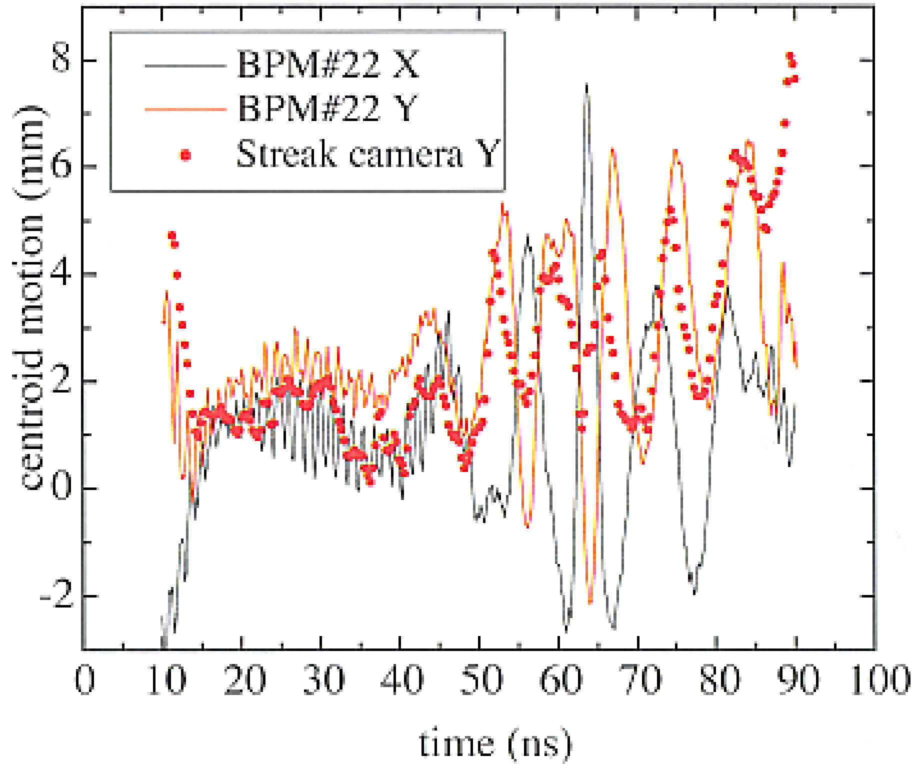
DARHT-I
- 66 cm drift space between 2 foils (long drift to amplify the ion effects)
- 19.8 MeV, 1.8 kA, 60 ns flattop
- ~ 1500 mm-mr
- 0.5 - 100 A/cm^2 on 1st foil
- 2 x 10^{-6} torr

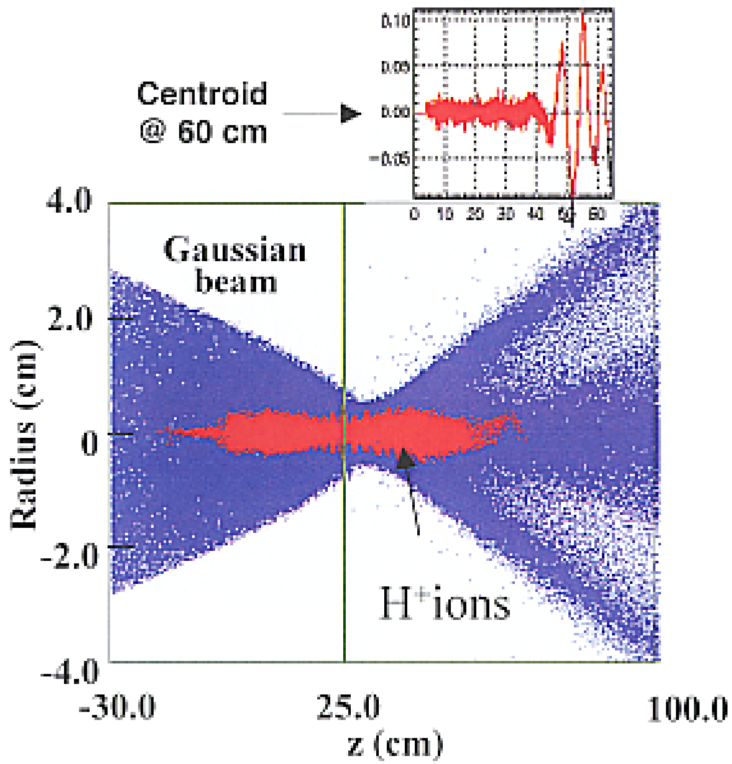
ETA-II
- Similar setup but 17 cm drift space between 2 foils (Lauer, et. al., BEAMS 2002)
- 5.7 MeV, 1.8 kA, 40 ns flattop
- ~ 1000 mm-mr
- 0.5 - 100 A/cm^2 on 1st foil
- 2 x 10^{-6} torr

Frequency of the transverse instability observed on the double-foil experiment on DARHT-I suggests significant H^+ ion component

Titanium foil: DT#1=240A.
f = 125 ± 10 MHz
Amplitude (p to p) = 6 ± 3 mm

LSP simulation:
Ion hose instability f = 140 MHz
Amp (p to p) = 2 mm

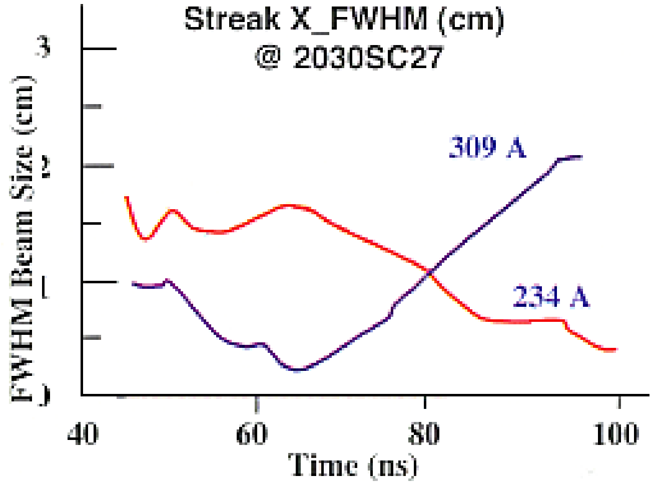




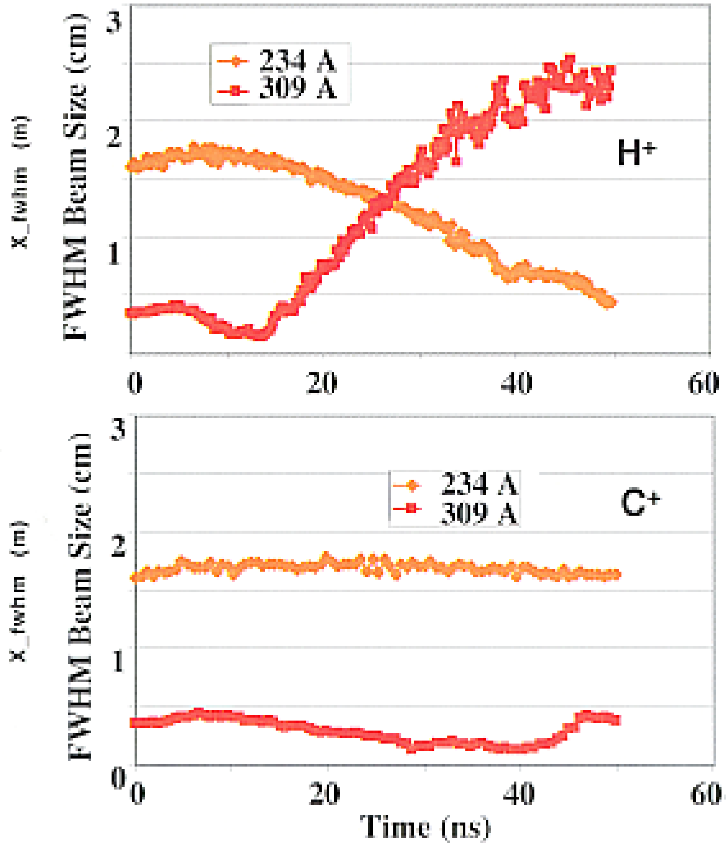
(* H. Davis, et. al., to be published by *Physics of Plasma*)

Simulations and ETA-II double-foil flashover experimental data suggest that ion channels were mainly formed by backstreaming protons

- Beam on quartz foil causes flashover early in the pulse
  - Provides "strong" source to compare with particle simulations with space-charge-limited emission for backstreaming ions



(J. McCarrick, 2002)
Simulations

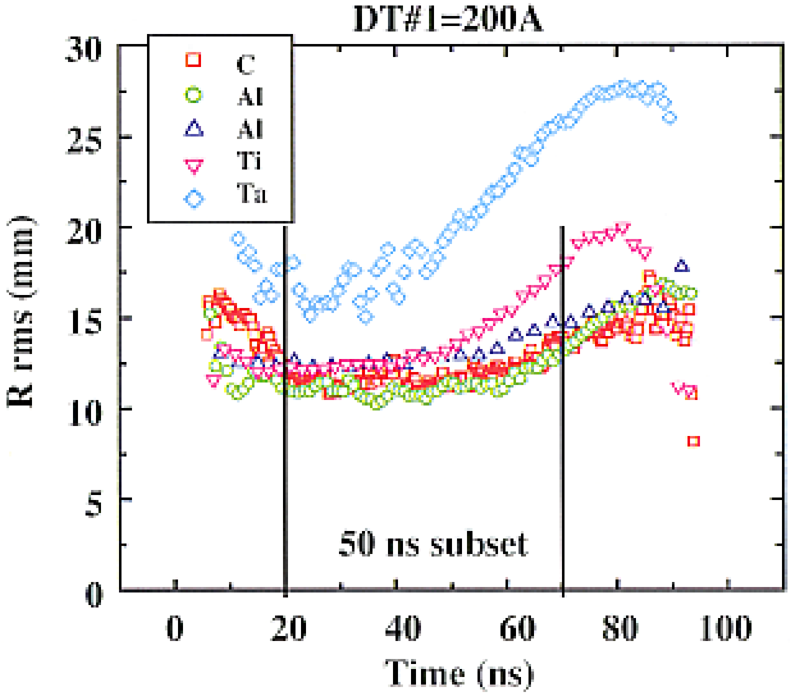


ETA-II:
6 MeV
2 kA
40 ns flattop
1000 mm-mr

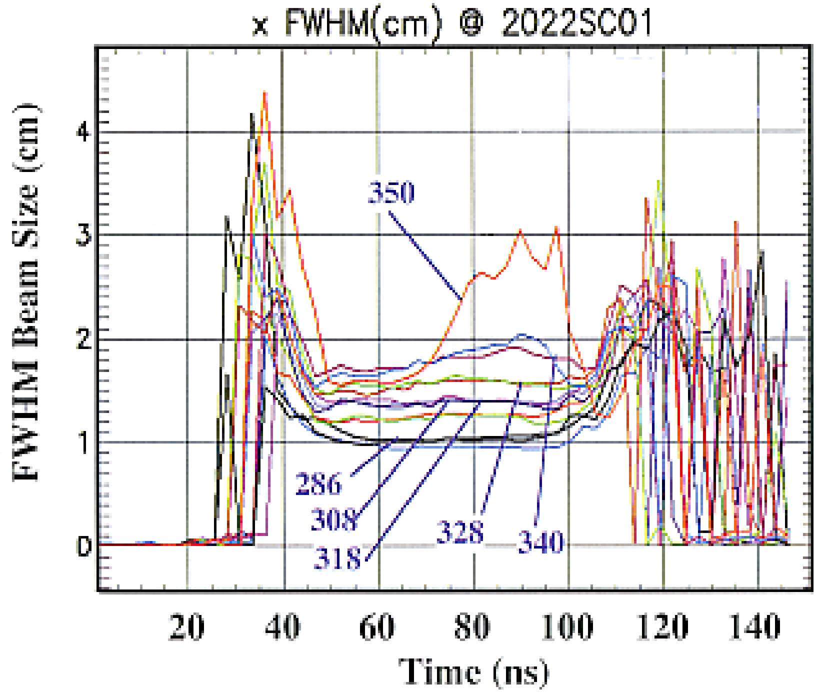
Time varying spot sizes due to backstreaming Ion effects were observed in double-foil experiments

- Observations:
  - The strongest effect were seen on DARHT with Ta & Ti foils
  - *Sufficiently* thin Ta not used on ETA exp'ts (Ti not at all)
  - With all materials, effect not observable over error bars within ETA flattop for beam radius ≳ 2 mm

(H. Davis, et. al., to be published by *Physics of Plasma*)



(Lauer, et. al., 2002)

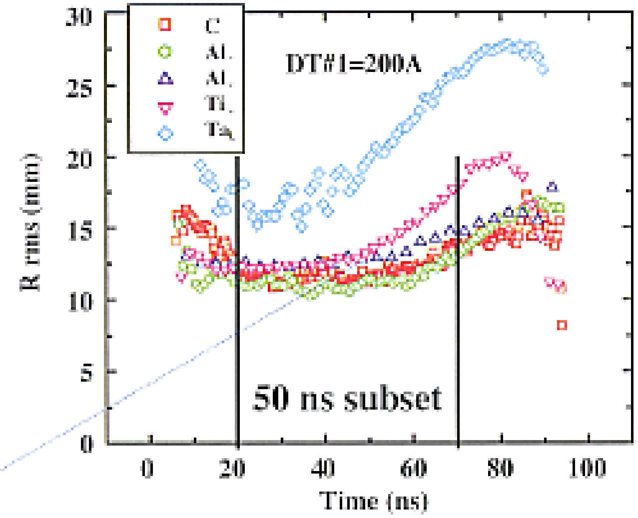


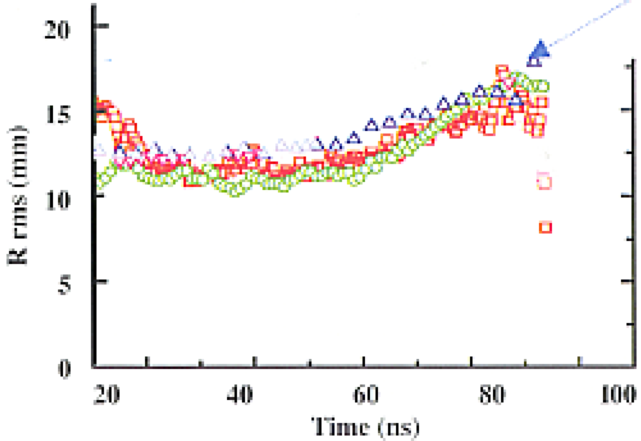
Matching simulations with DARHT-I and ETA-II double-foil experimental data suggest that ion emission from foils may be source limited

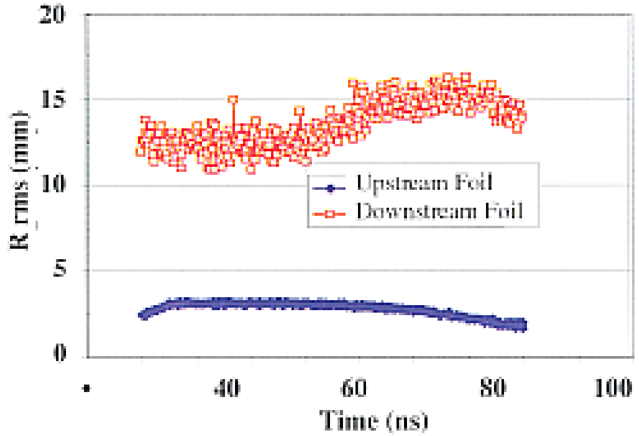
- Simulations include (J. McCarrick, 2002)
  - Gas desorption model
    $dN/dt = \nu (N_s - N) exp(-E_b/T)$
  - Impact ionization (H_2 only)
    $dN_i/dt = \sigma N J_b/q$

  $\sigma = 2.5e\text{-}19\ cm^2$ for H_2 -> H_2^+ at 20 MeV
  - Ionization by backscattered electrons
    ⇒ insignificant
  - Varying E_b and N_s to match the data
- **Best fit: $E_b = 0.47$ eV, $N_s \sim 3\times10^{15}\ cm^{-2}$ (~ 40% of SCL H^+)**
- ETA-II pulse (40 ns) is too short to observe beam blow-up

DARHT-I Data







DARHT-I double-foil experimental data can also be explained with ionization of water vapor

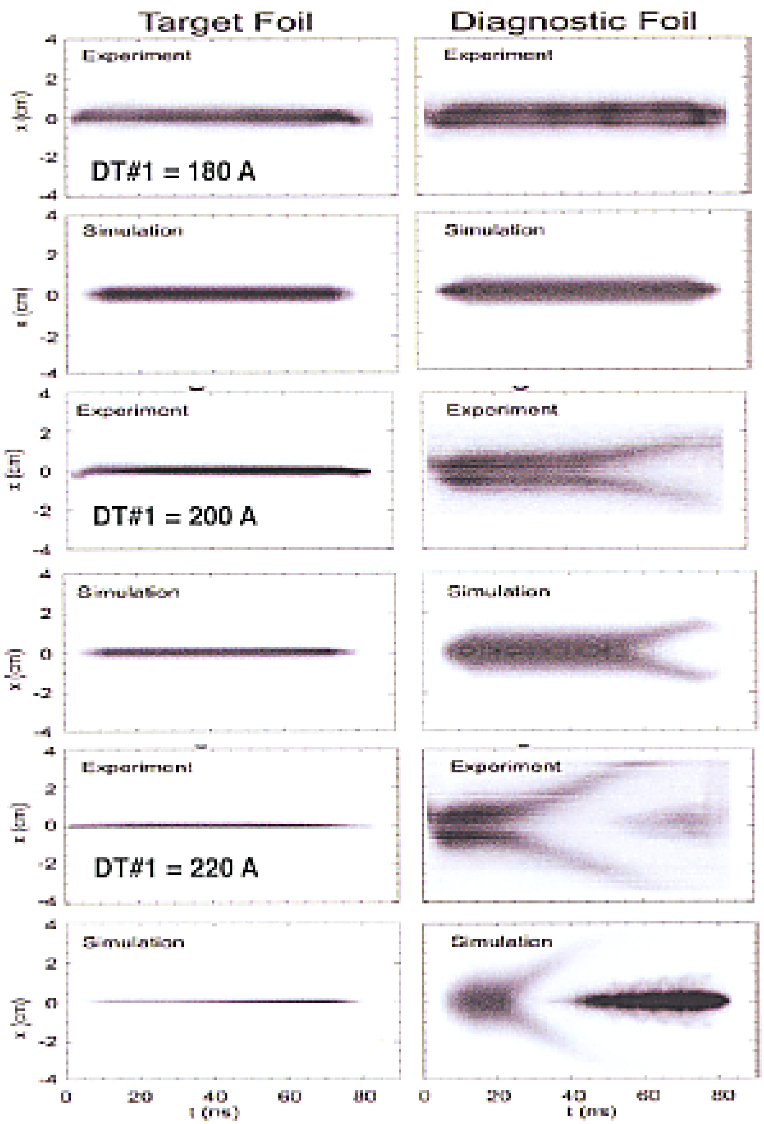
- PIC simulations also match data well by assuming that the source of ions is absorbed water

  (H. Davis, et. al., to be published Phys. of Plasma)

  - 91 % of ions are H_2O^+, OH^+, O^+ (mass ~ 16-18 AMU)
  - 9 % of ions are H^+
  - Extrapolate the impact ionization data for 10 - 1 kV electrons to 20 MeV
  - Space charge limited emission of the mixture yields 40% of the current in H^+

- Spot size disruption was never observed on the target foil even for small beam spot (1.5 - 2.5 mm FWHM)

  - Backstreaming ion effect may not be an issue for a 20-MeV single pulse x-ray radiography facilities?



Mitigation

Backstreaming ion effects can be minimized by using a foil to confine backstreaming ions in a short distance

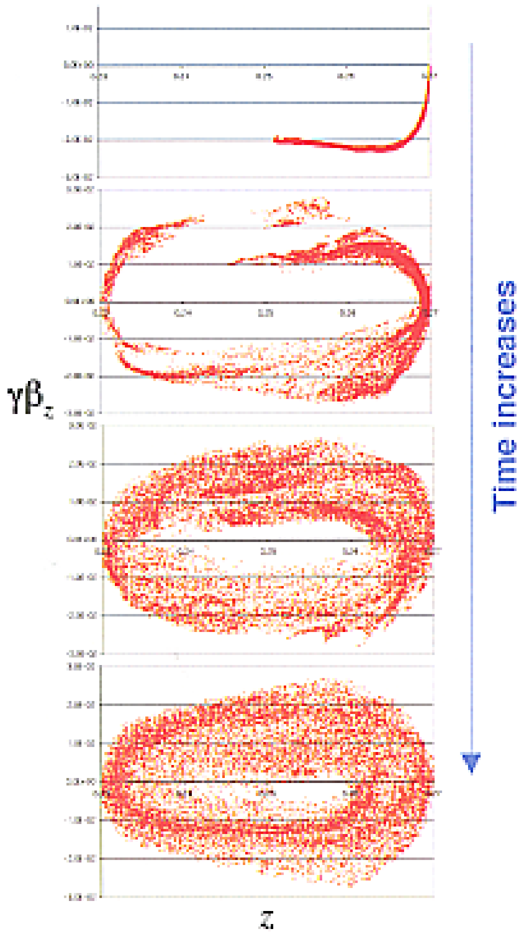
- Ions are trapped between the grounded target and the grounded foil electrostatically (T. Highes, 1998)
- The foil-target separation depends on beam envelope and neutralization profile

$$L_D \approx a\sqrt{\frac{\pi\gamma\beta^2 I_o}{f I}}$$

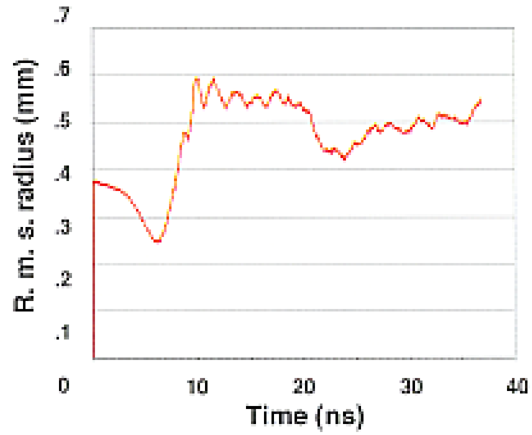
- Trap has a finite fill time
  - Time-dependent neutralization profile $f(z, t)$
    - ⇒ f > 1 near the foil and the target
  - Asymptotically approaches to f = 1 everywhere
  - Beam spot behavior has transient
- Positively bias the target does not change the spot size transient behavior

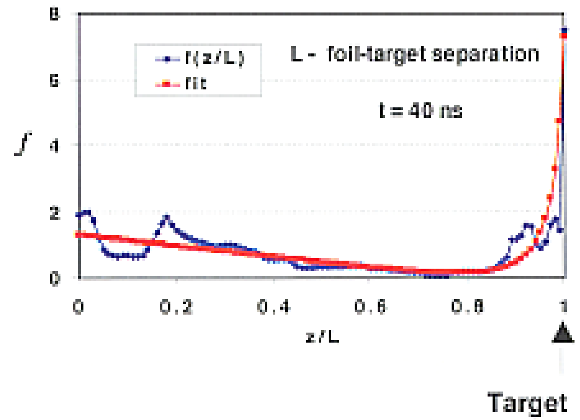
PIC simulations by J. McCarrick (2002)

Time evolution of ion longitudinal phase space



Time varying spot size on target

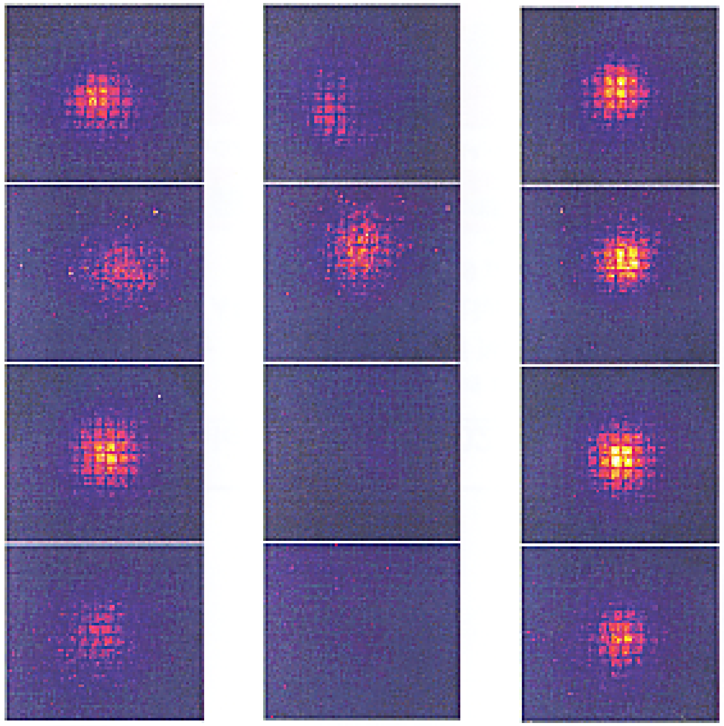




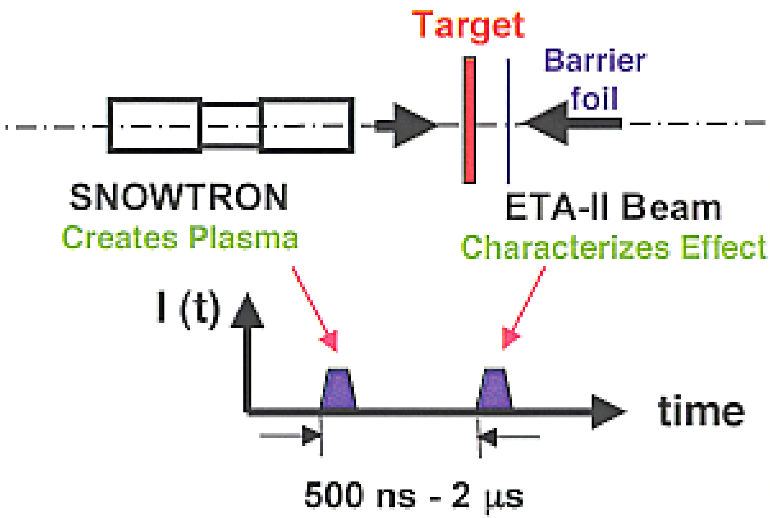
ETA-II/SNOWTRON experiments show that a barrier foil can suppress time varying spot size growth*

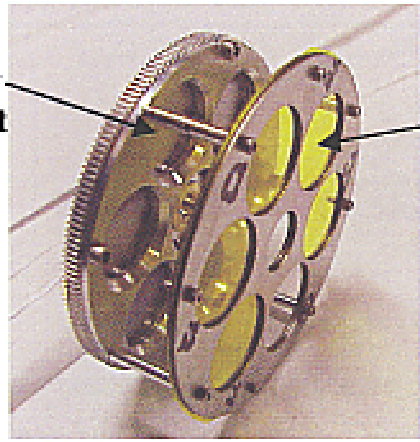
Each pixel is 0.25 mm square

ETA-II x-ray spot size



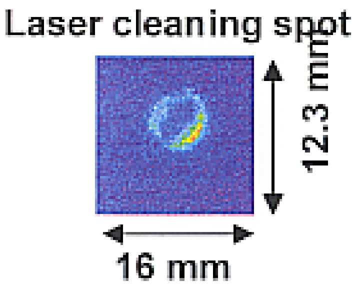
	SNOWTRON not fired, No Barrier Foil	SNOWTRON fired, No Barrier Foil	SNOWTRON fired, Barrier Foil
0-10 ns			
10-20 ns			
20-30 ns			
30-40 ns			

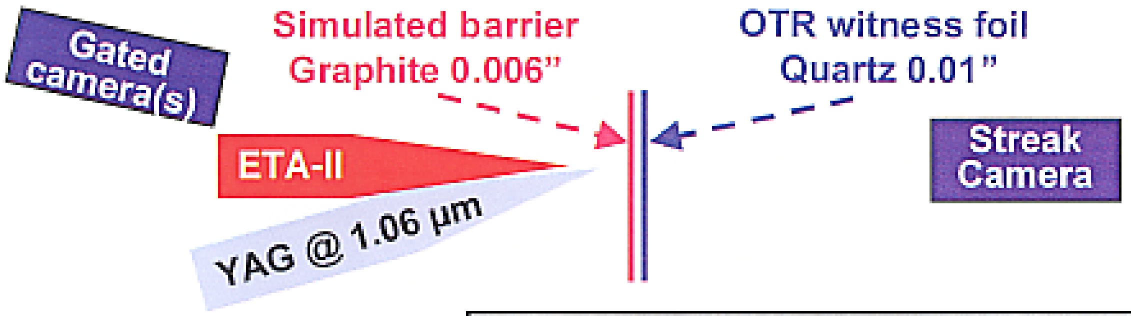




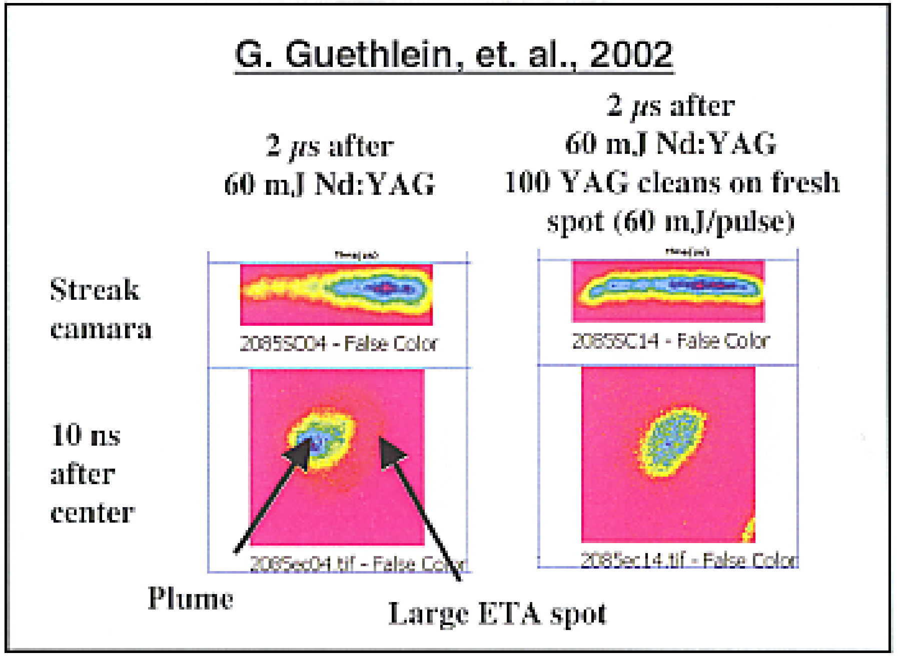
* S. Sampayan, et. al., 2001

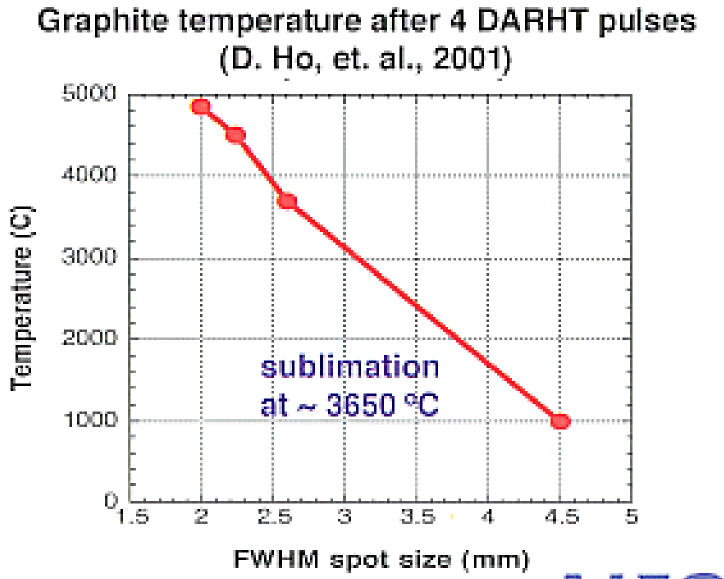
Laser cleaning can minimize backstreaming ion emission and prevent spot size disruption





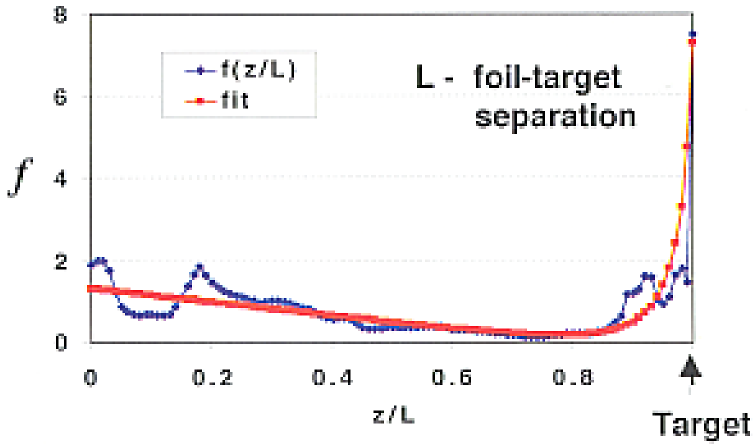
- Graphite foil can be used as a foil-barrier on DARHT-II
- Ions maybe emitted from the upstream face if not *pre-cleaned*





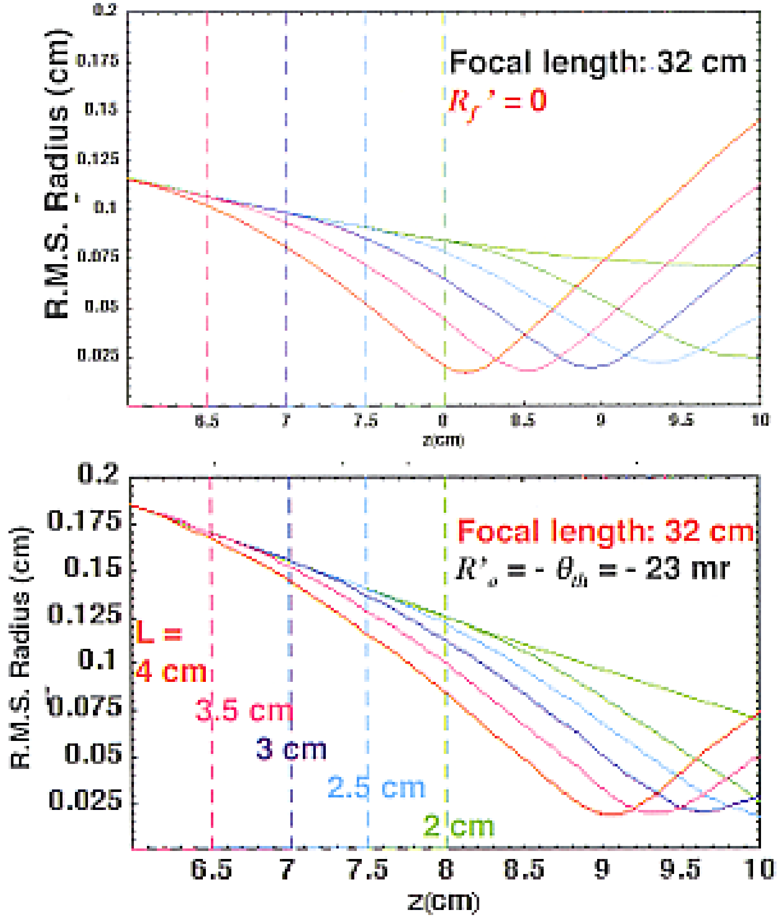
The required foil location and spot size on foils are sensitive to the nominal beam envelope near the target

- The envelope equation is solved
  - uses the neutralization obtained from PIC simulations for foil barriers
  - Space charge limited emission for H^+ is assumed in PIC calcs
- However, all the PIC simulations suggest the H^+ emission rate to be only ~ 30 - 40 % of the space charge limited emission rate



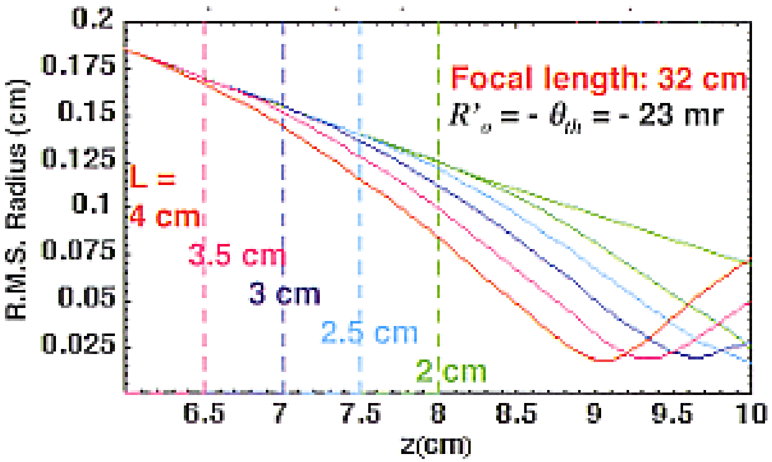
(Y.-J. Chen and G. Caporaso, 2001)

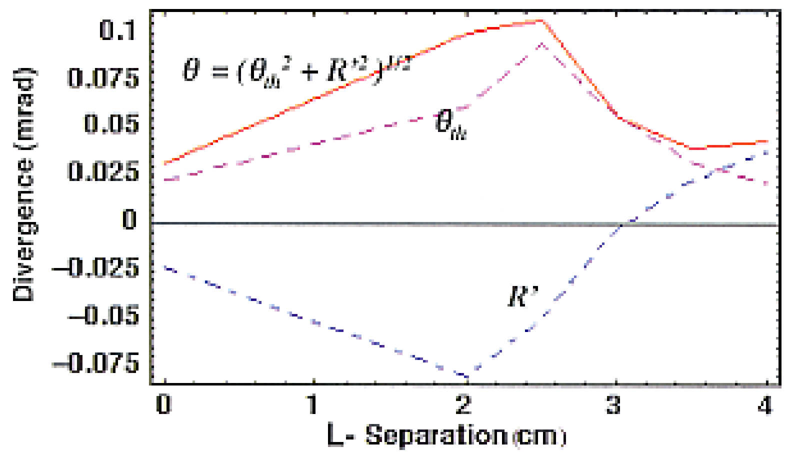
Beam envelopes with various foil locations, for two divergence conditions on the target



Performance of foil-barrier can be improved without sacrificing the final spot size and the x-ray dose by using different focusing schemes

- Focusing the beam beyond the target front surface
  - Larger beam envelope in the trap region
  - Larger spot size on the foil
  - Better foil-barrier performance
- The forward x-ray dose is not a strong function of beam divergence at the target (Y.-J. Chen and E. R. Rose, 2000)
  - 2.1 mm diameter, 18.4 MeV, 1500 p mm-mr: $\frac{\Delta D}{D} \approx -20\% \frac{\Delta\theta}{\theta}$
- Dose reduction due to envelope divergence can be compensated with longer pulse
  - However, the reduction due to emittance growth from foil scattering and nonlinear ion focusing forces may be an issue





Summary: Controlling the beam-target interactions is paramount to x-ray flash radiography facilities

- Ions in the DARHT-I and ETA-II double-foil experiments
  - The largest *q/m* ions dominate the backstreaming ion focusing effects
  - Source limited H^+ (~ 30 % space-charge-limited emission rate)
  - 91 % of ions are H_2O^+, OH^+, O^+ and 9 % of ions are H^+ (40% of ion current)
- Backstreaming ion effects can be minimized by
  - Pre-cleaning the surface with electron beam pulses or laser pulses
  - Trapping ions with a grounded foil
    - Performance of the system is sensitive to
      - √ Foil location, ion neutralization profile & beam envelope
    - Short foil-target spacing and large beam envelope are preferable
      - ⇐ Ion emission rate is difficult to predict
      - ⇐ The foil-barrier scheme may not be suitable for short beam pulses due to ion transient effect
    - Dose reduction
      - √ Due to envelope divergence/convergence at target is not serious
      - √ Due to emittance growth from foil scattering and nonlinear ion focusing forces may be an issue

Ions can be liberated by several processes

Decreasing beam radius ↓

- Electron impact induced desorption of ions and neutrals
  - Single particle effect – independent of beam radius
  - Neutral particle yields up to 5 possible on uncleaned surfaces
- Thermal desorption of impurities from the surface [*Sanford(1989)*]
  - Requires heating of foil by the beam to on the order of 400°C for binding energies of about 1eV
  - Neutrals are ionized by the beam
- Melting (or sublimation for carbon) followed by ionization Similar to thermal desorption, but requires higher temperatures.

Decreasing beam radius ↓