# Assisted Pinch mode for heavy ion beam transport

## *Experiments & Simulation Results and Plans*

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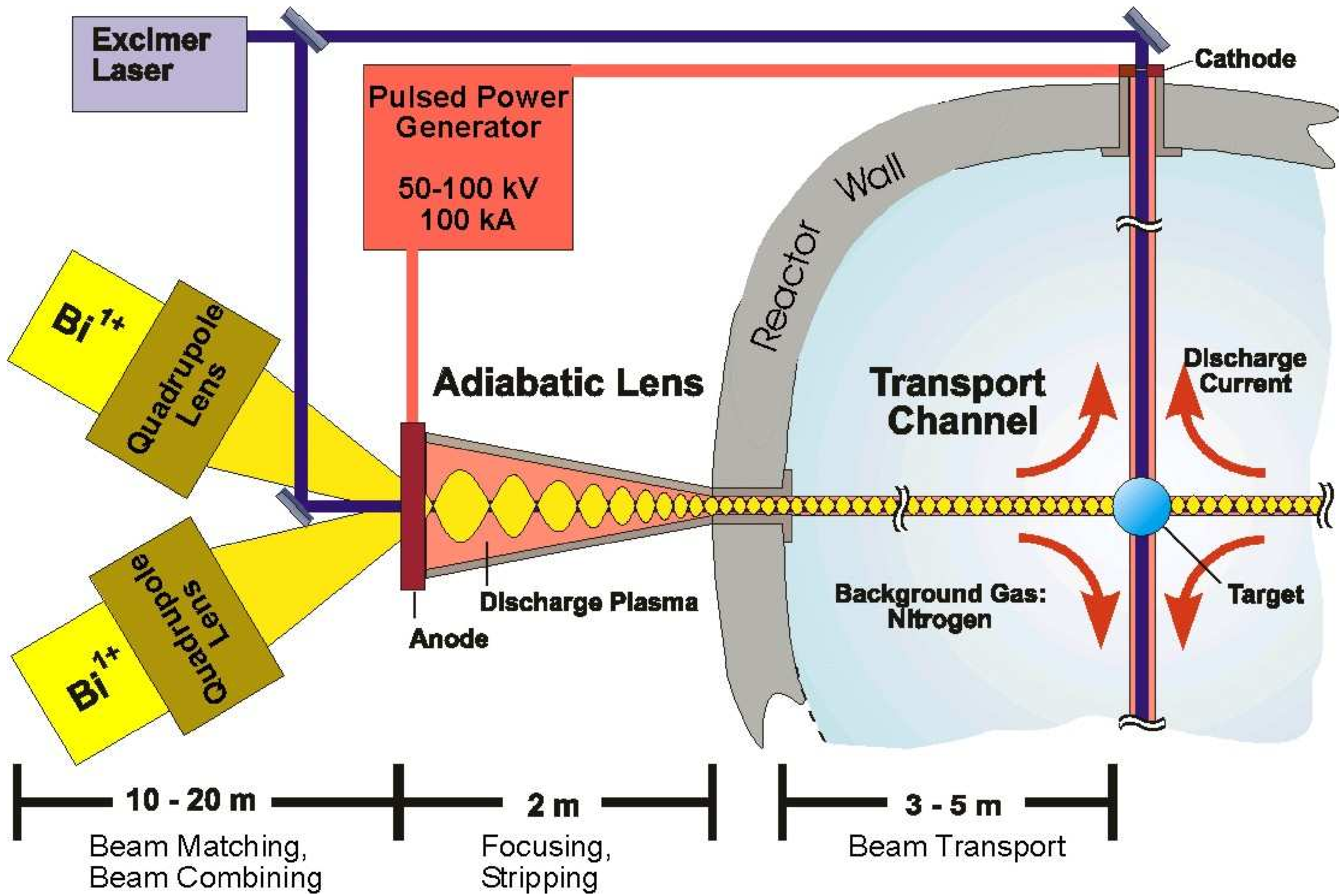
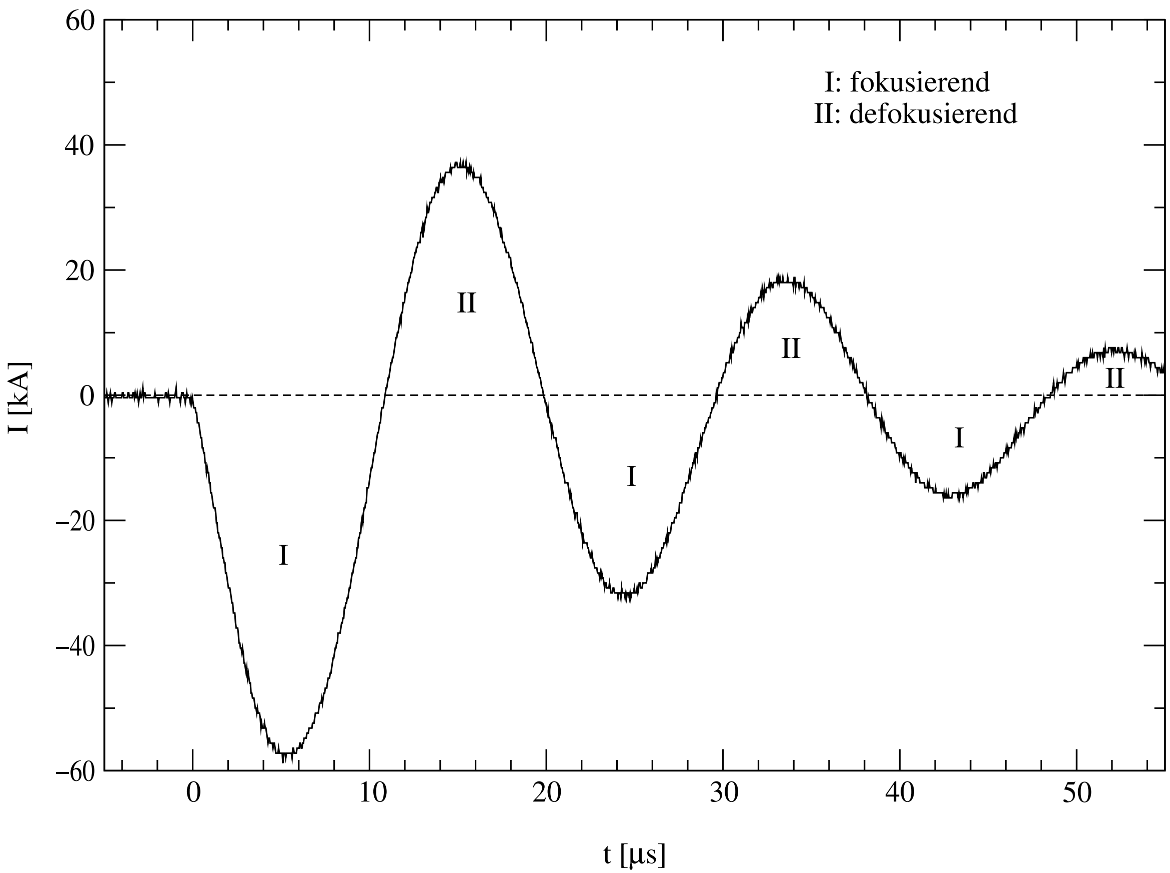
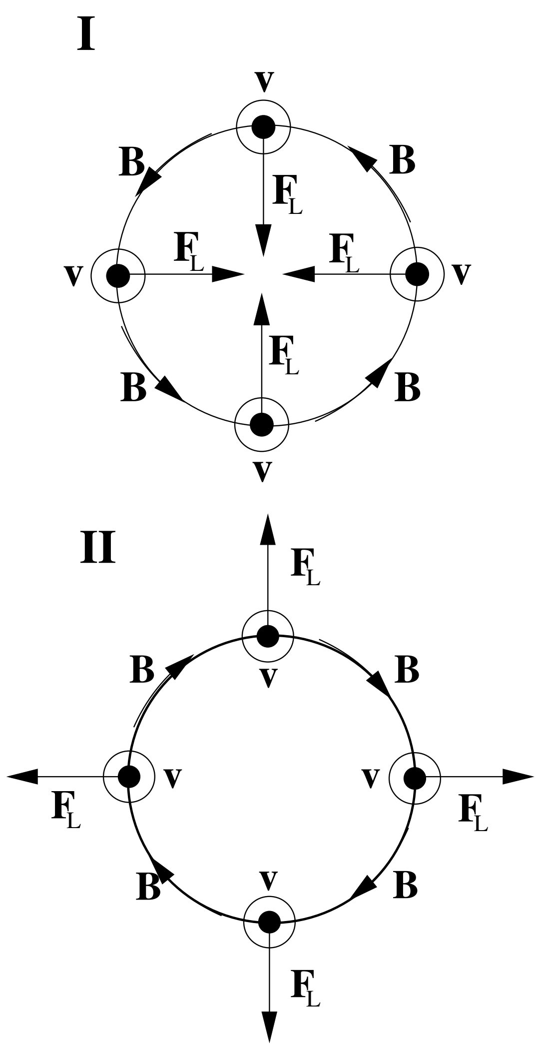
# Reactor concept



# Basics of channel transport




$$B(R_{\mathsf{ch}}) = \mu_0 \cdot I/(2\pi R_{\mathsf{ch}}) = 2.4\,\mathrm{T} \text{ for } R_{\mathsf{ch}} = 5\,\mathrm{mm},\ I = 60\,\mathrm{kA}$$

# Conditions for beam transport

- prevent breakdowns to the walls
  $\longrightarrow$ sufficient rarefaction on axes
- minimize energy loss in the channel
  $\longrightarrow$ upper limit for density on axis
- limit channel clearance by $\mathbf{j} \times \mathbf{B}$ force
  $\longrightarrow$ lower limit for density on axis

$\longrightarrow$ results in a pressure window for chamber operation
$\longrightarrow$ ongoing: **map out pressure window** (calculations and simulation runs)

# Necessary rarefaction

Breakdown condition for xenon:

$$(E/p)_{\text{Xe}} = 60\,\text{V}/(\text{cm Torr})$$

Prevent breakdown to chamber wall:

$$(E/p)_{\text{channel}} > (E/p)_{\text{Xe}} \text{ and } (E/p)_{\text{chamber}} < (E/p)_{\text{Xe}}$$

$\rightarrow$ criterion for rarefaction:

$$\frac{n_{\text{channel}}}{n_{\text{chamber}}} < \frac{R_{\text{port}}}{R_{\text{chamber}}} = x$$

with $x$ chosen to be $\leq 0.1$

# Channel clearance

Ion beam induces return current $\rightarrow$ $\mathbf{j} \times \mathbf{B}$ force

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B}$$

$\rightarrow$ lower limit for gas density on axis
Estimate: neglect pressure term

$$\Delta x = \left( \frac{\mu_0 \, I_{\text{beam}} \, I_{\text{net}}}{4\pi^2 R_0^3 \, \rho} \right) \, t^2$$

Example:
$I_{\text{net}} = 50\,\text{kA}$, $I_{\text{beam}} = 3\,\text{MA}$, $R_0 = 5\,\text{mm}$, $t = 10\,\text{ns}$,
$\Delta x \leq 1\,\text{mm}$:

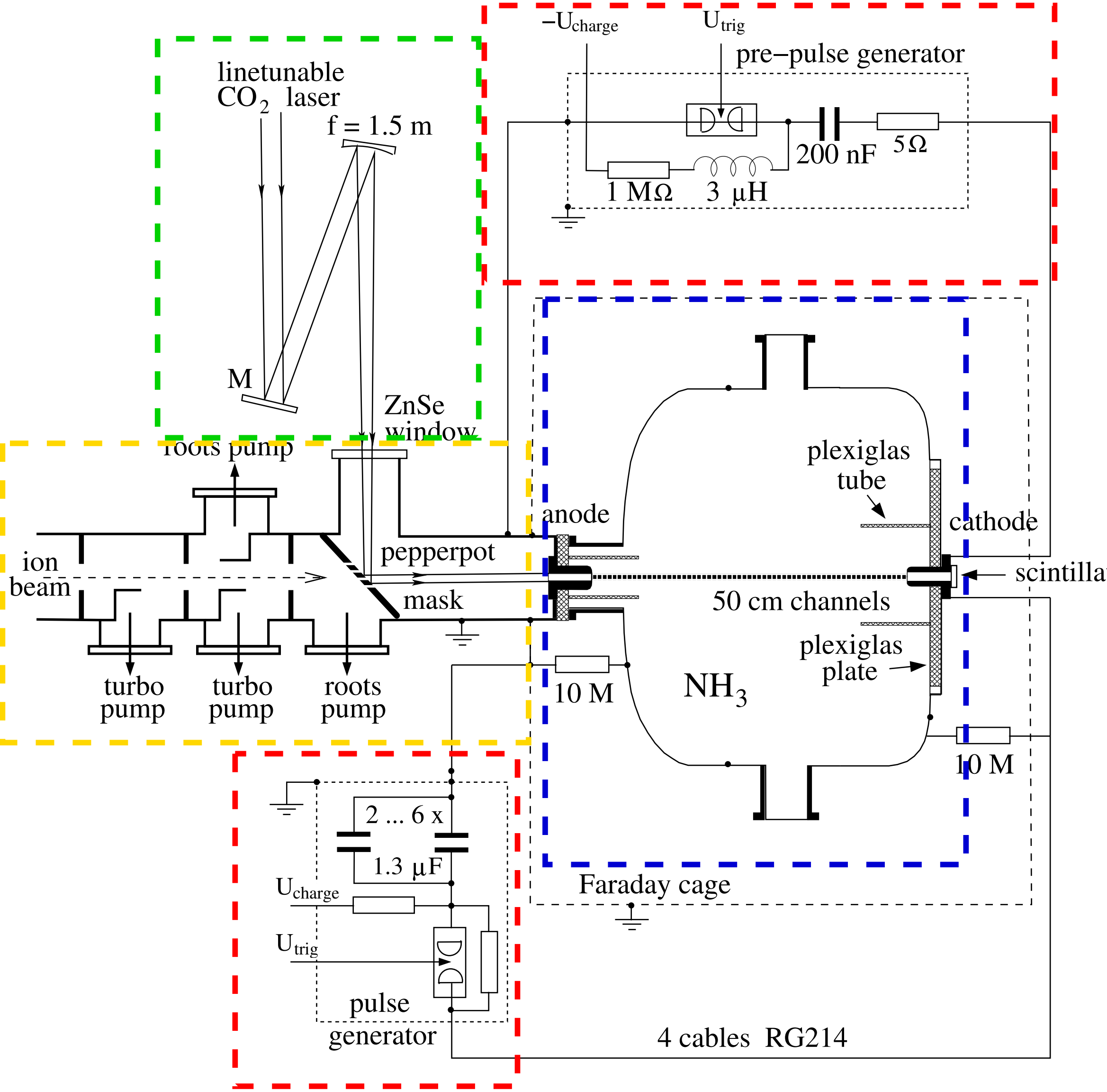
$$\rho \geq 3.8 \cdot 10^{-3}\ \text{kg/m}^3\ (0.5\,\text{Torr})$$

# Experimental setup

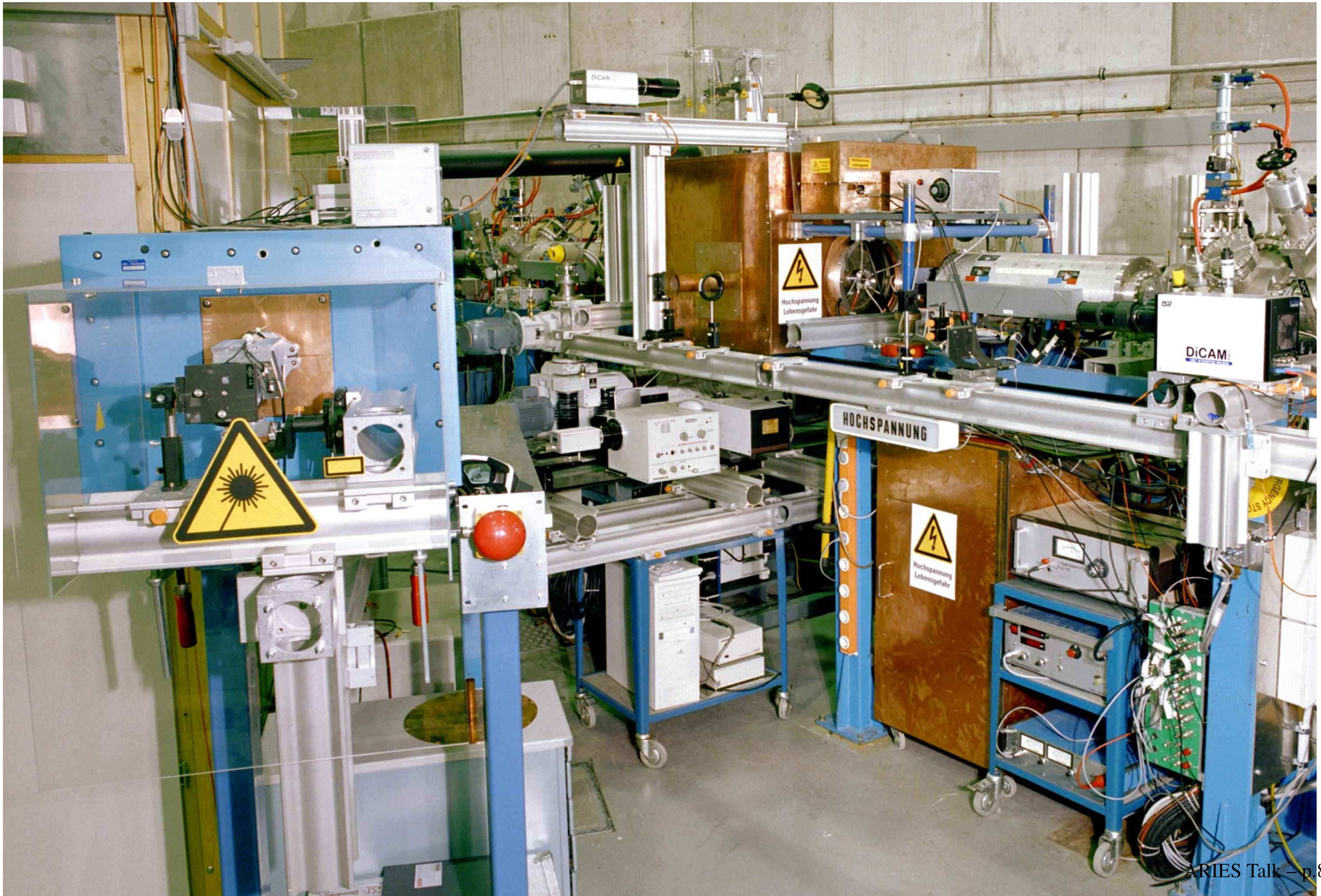
**Main parts:**

- **Discharge chamber**
- **Pulse generators**
- **Differential pumping section**
- **Carbondioxide laser**
- **Diagnostics (not shown)**

**Creation of crossed–channels also possible**



# Experimental setup II



# Diagnostics

Wide variety of used diagnostics

- Photographic images of the discharge → control stability of the discharge
- Scintillator → determine beam transport properties
- Interferometer → determine electron density
- Spectroscopy → determine electron density and electron temperature
- Heavy ion beam → determine development of gas density after heating
- Inserted probe → determine current density
- Faraday rotation → determine magnetic field (LBNL)

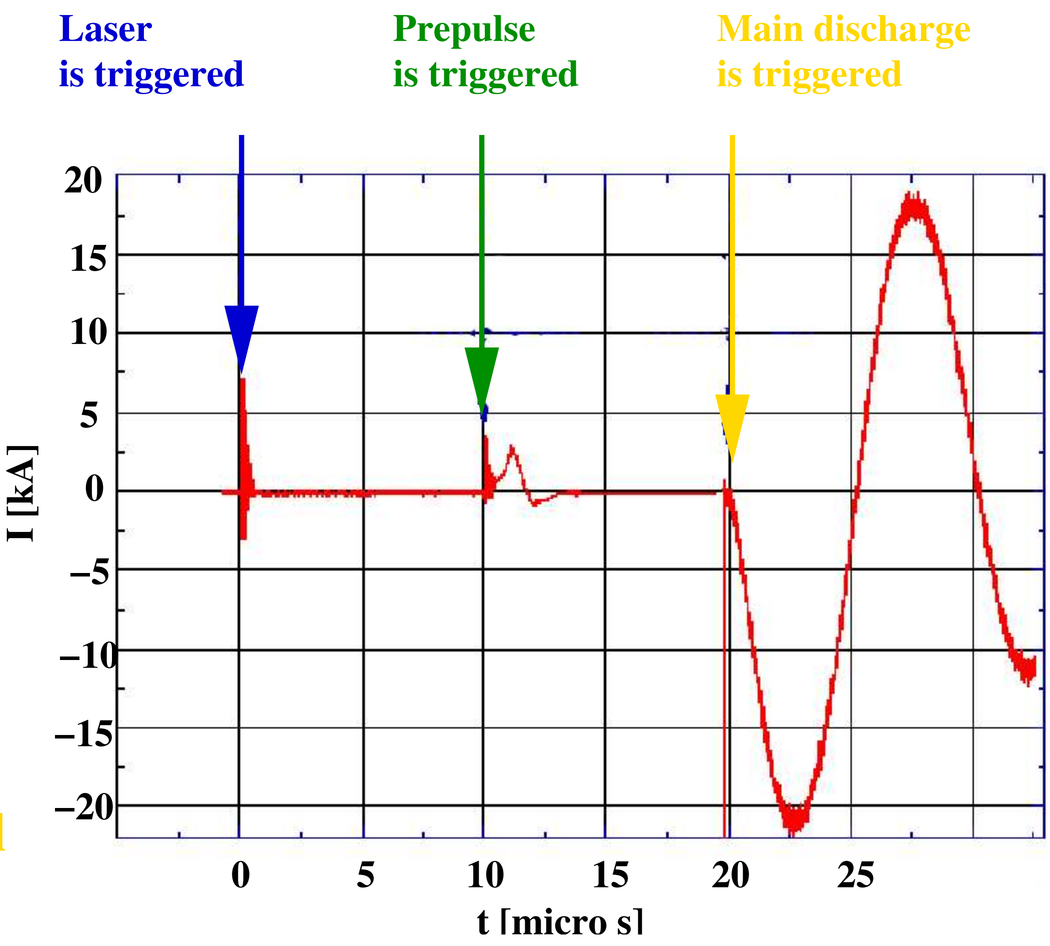
# Channel creation

**Three steps:**

1) **Laser:**
   **Energy: 5 J**
   **Heating leads to rarefaction on axis**

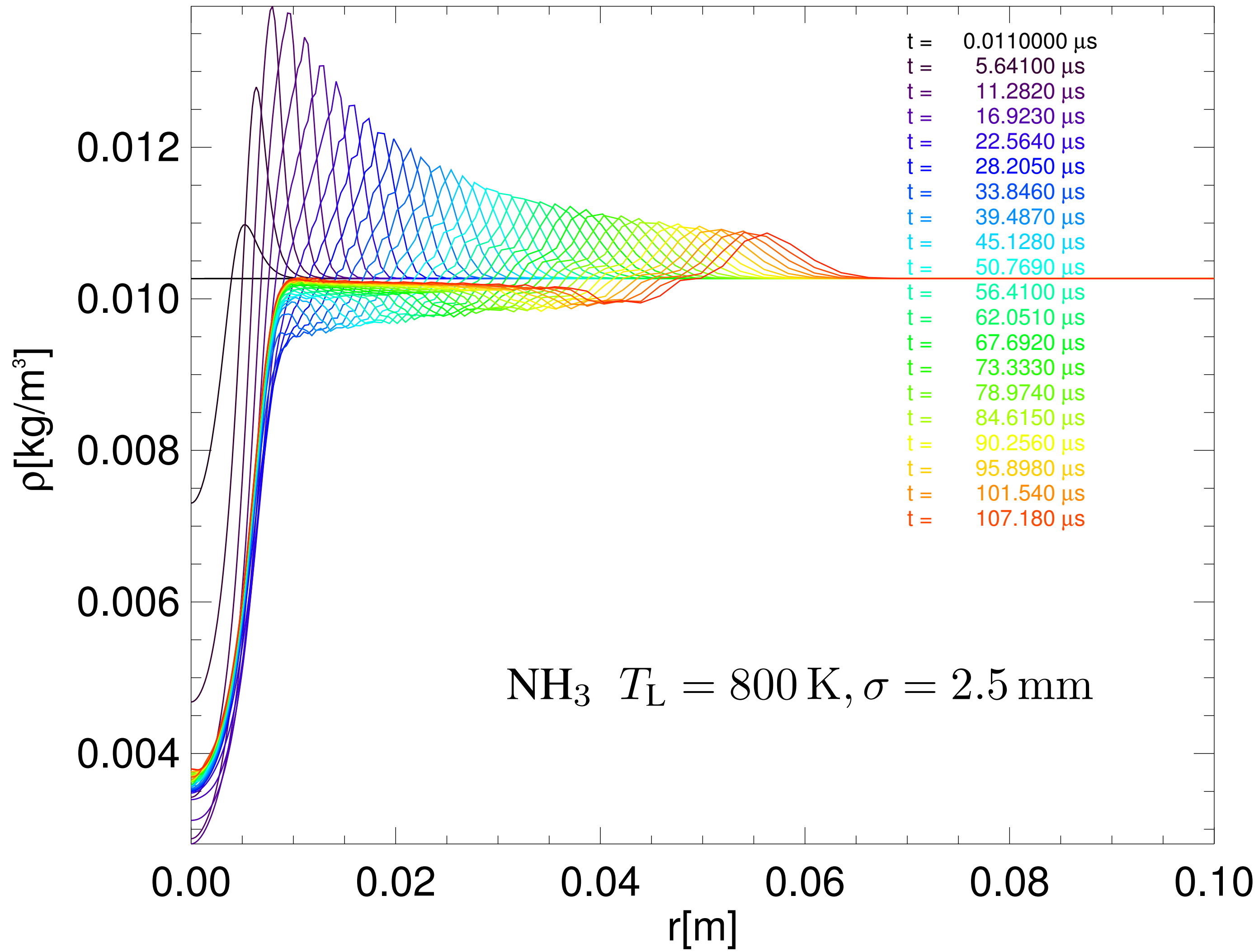
2) **Prepulse**
   **Energy: 40 J**
   **Further rarefaction, Ionization**

3) **Main discharge**
   **Energy: 3 kJ**
   **Create plasma channel**

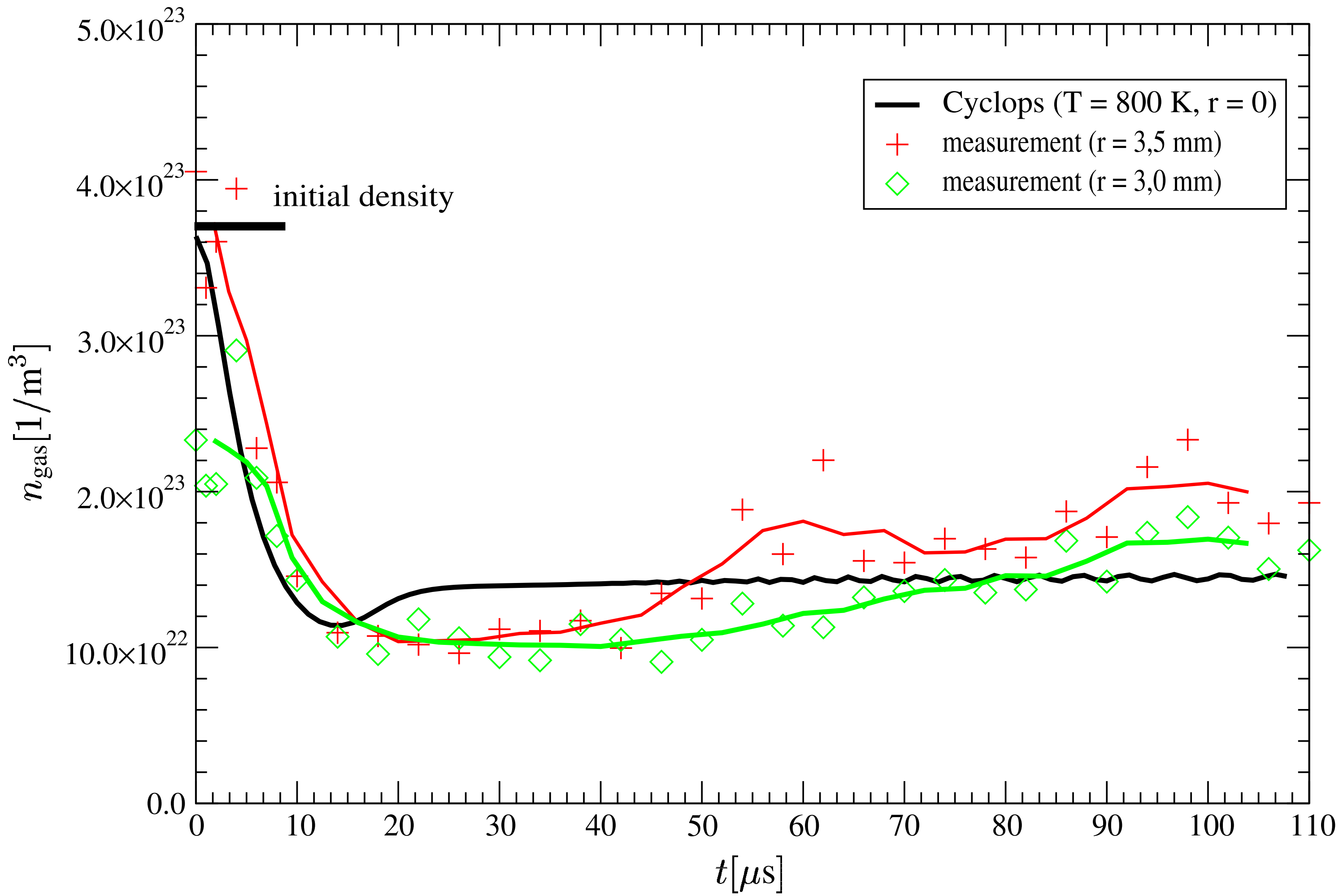


# Laser - Heating & rarefaction

$$T(r, t = 0) = T_0 + T_L \cdot \exp\left[-r^2 / \left(2\sigma^2\right)\right]$$



# Laser - density on axis

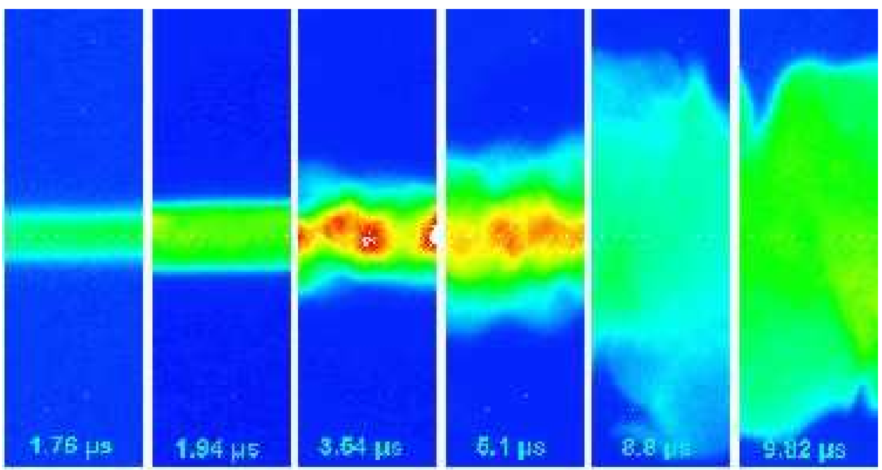



→ good agreement between simulation and measurement

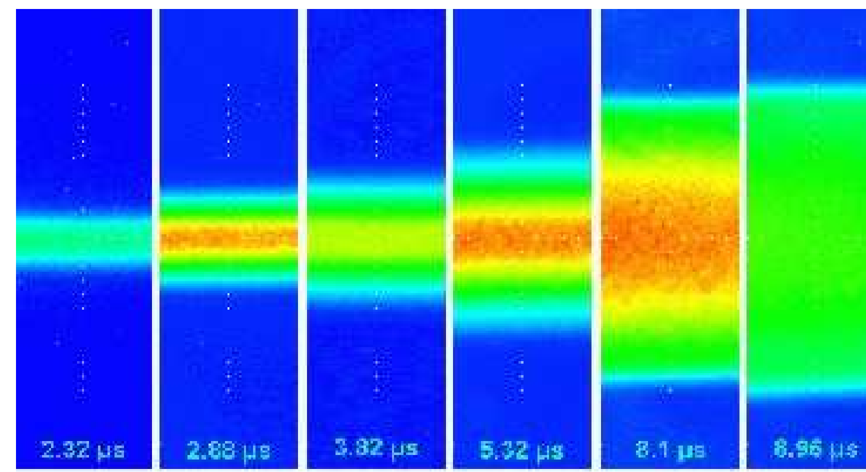
# Prepulse

Serves to stabilize the main discharge

**Discharge in 20 mbar ammonia**
**20 kV / 45 kA**
**without prepulse**




**Discharge in 20 mbar ammonia**
**20 kV / 45 kA**
**with 3 kA prepulse**

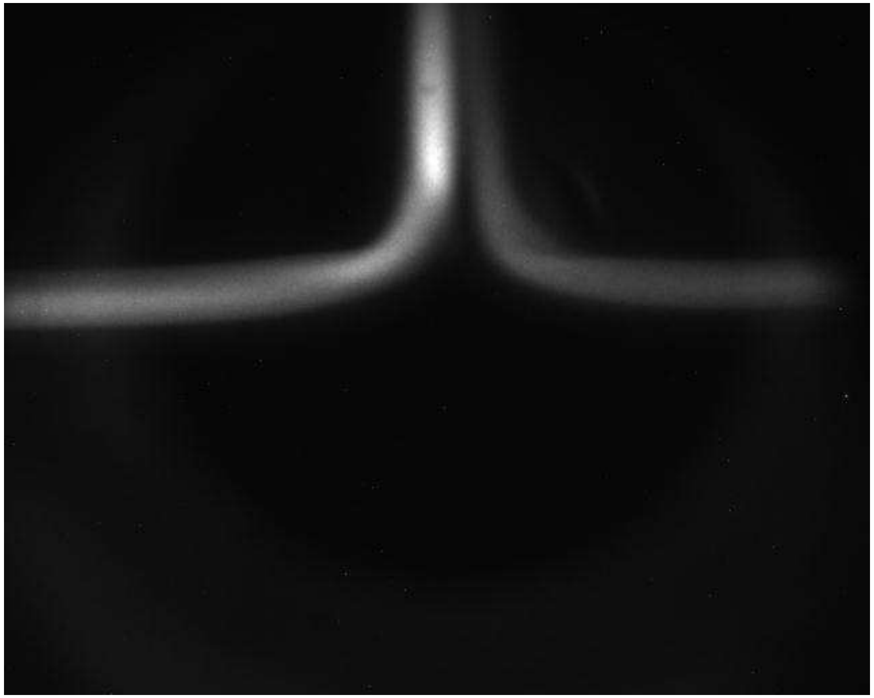


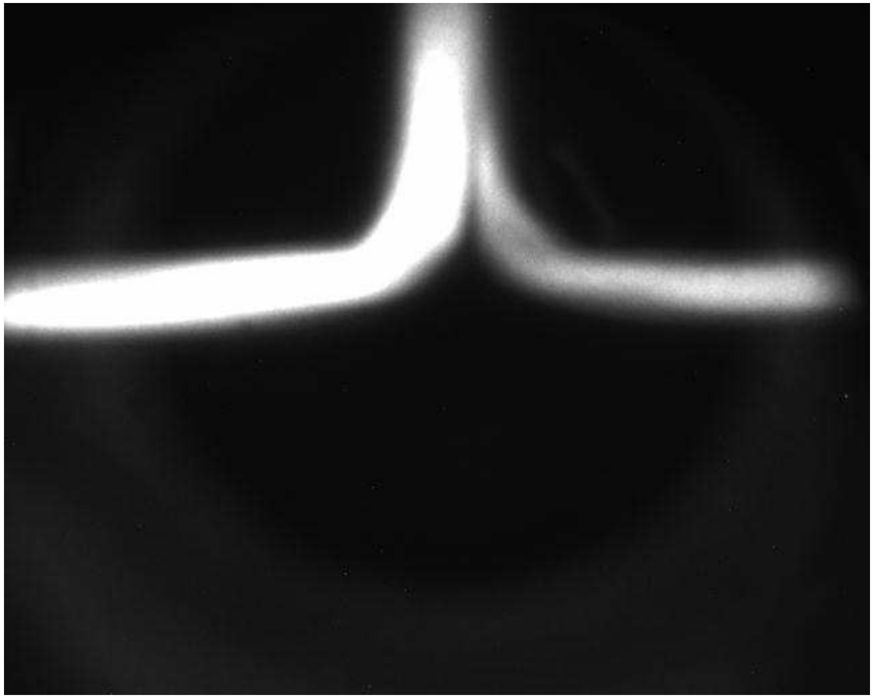

Growth rate for kink instability

$$\Gamma_{\text{kink}} \propto \frac{B_\theta}{\sqrt{\rho_{\text{ch}}}} \left( \frac{\rho_{\text{ch}}}{\rho_{\text{g}}} \right)^{0.5}$$

# Crossed channels

**Beginning** **Current maximum**

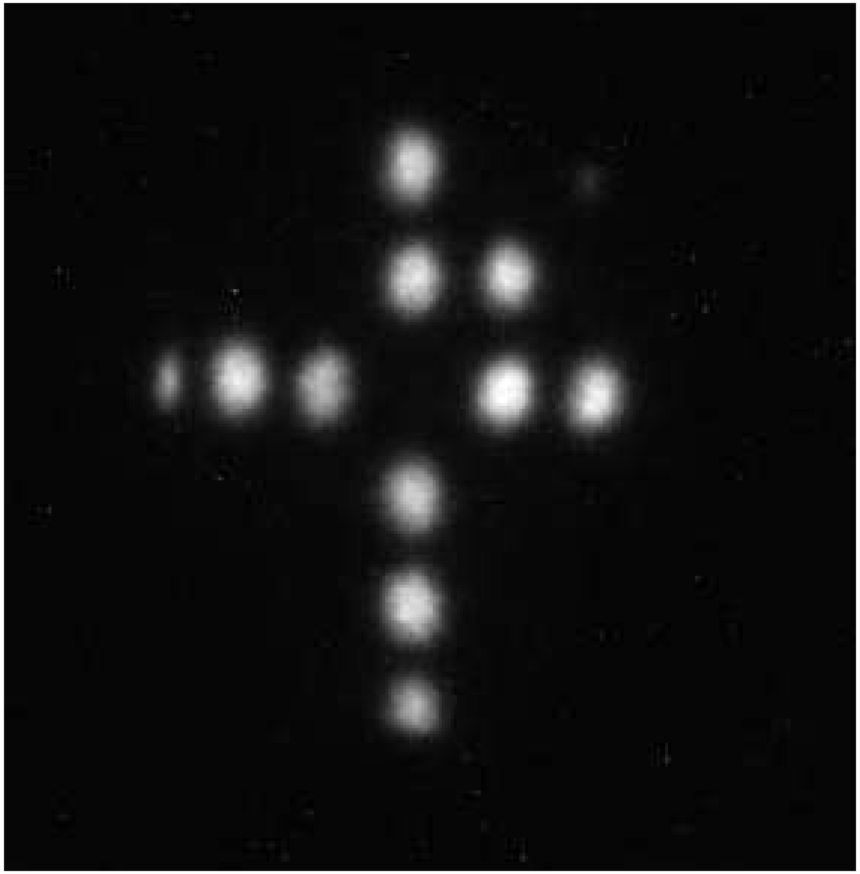




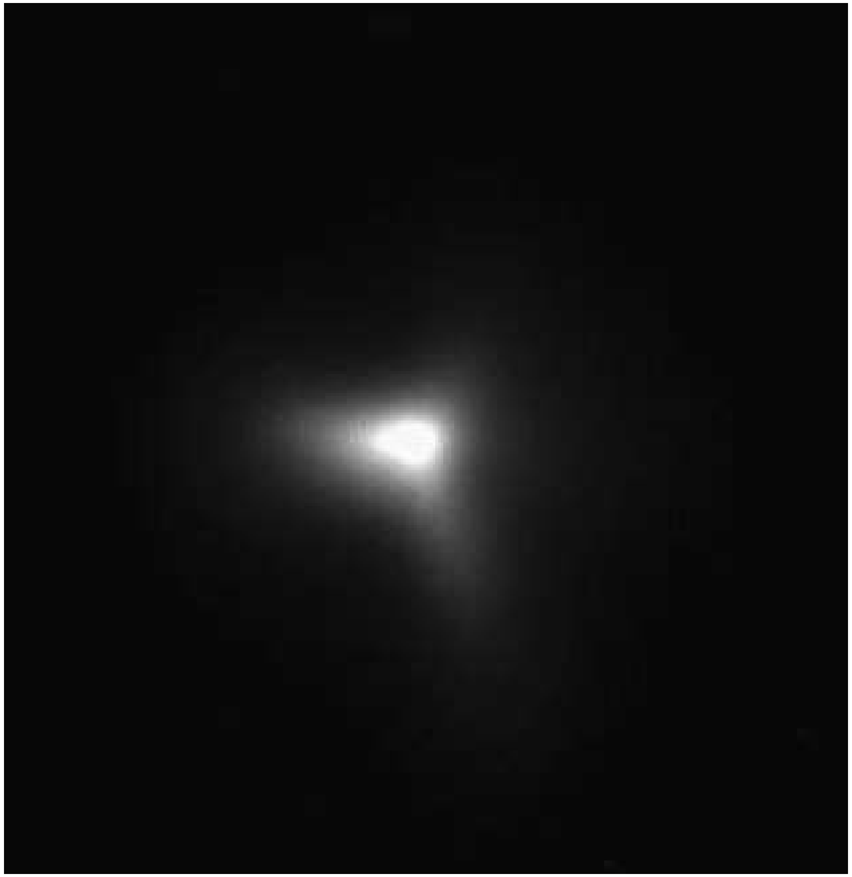
- discharge follows laser paths

# Beam transport

**Unfocused Beams**

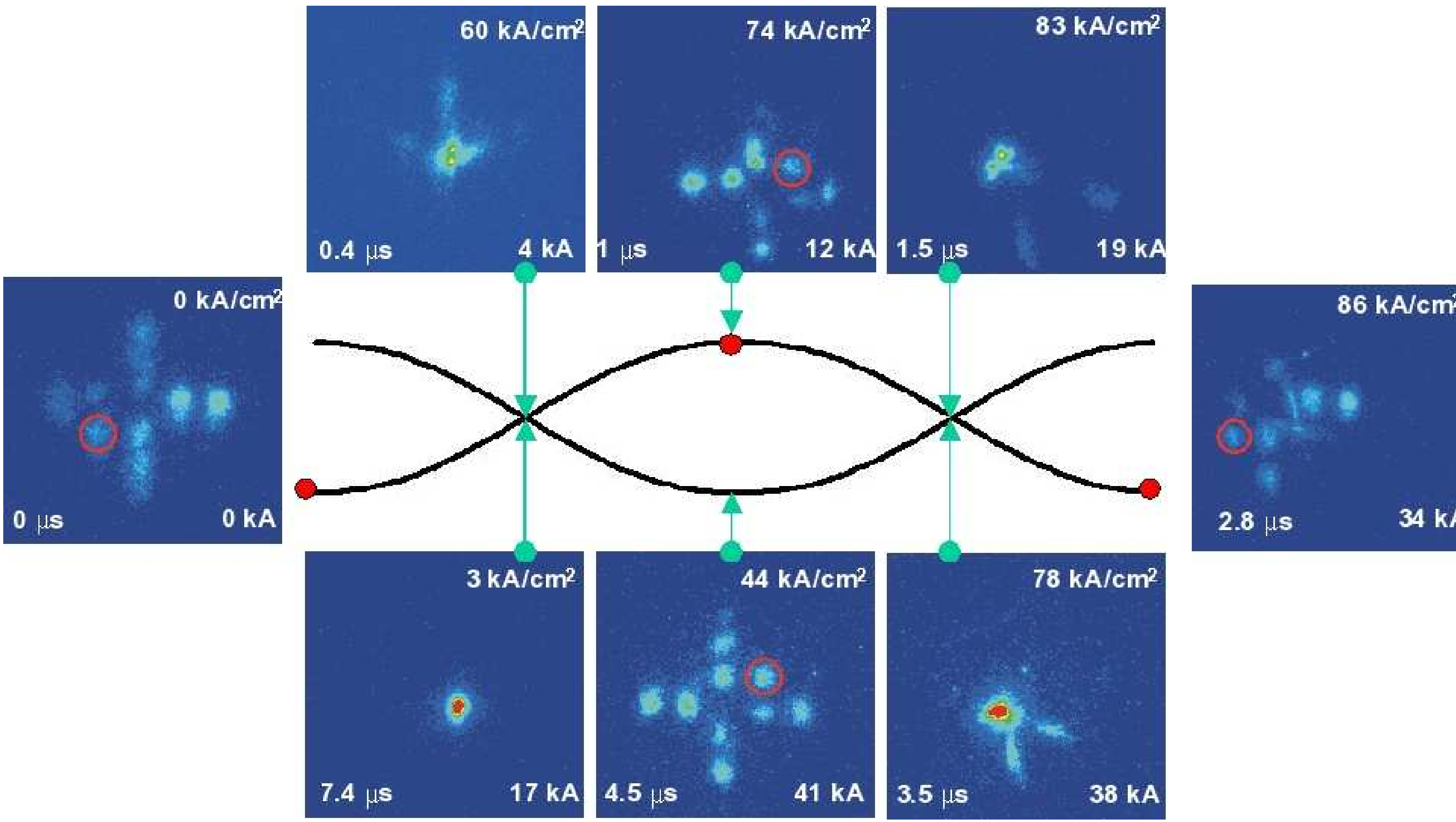


**Focused Beams**



size of the cross: about $1\,\mathrm{cm} \times 1\,\mathrm{cm}$

# Beam transport II



# Conclusions & Outlook

Achievements so far:

- stable channels
- creation of crossed channels possible
- good agreement between simulation and experiment
- various diagnostics used

Still necessary:

- channel prolongation
- using xenon instead of ammonia
  $\rightarrow$ use of PHELIX laser
- higher beam currents