Assisted Pinch mode for heavy ion beam transport

Experiments & Simulation Results and Plans

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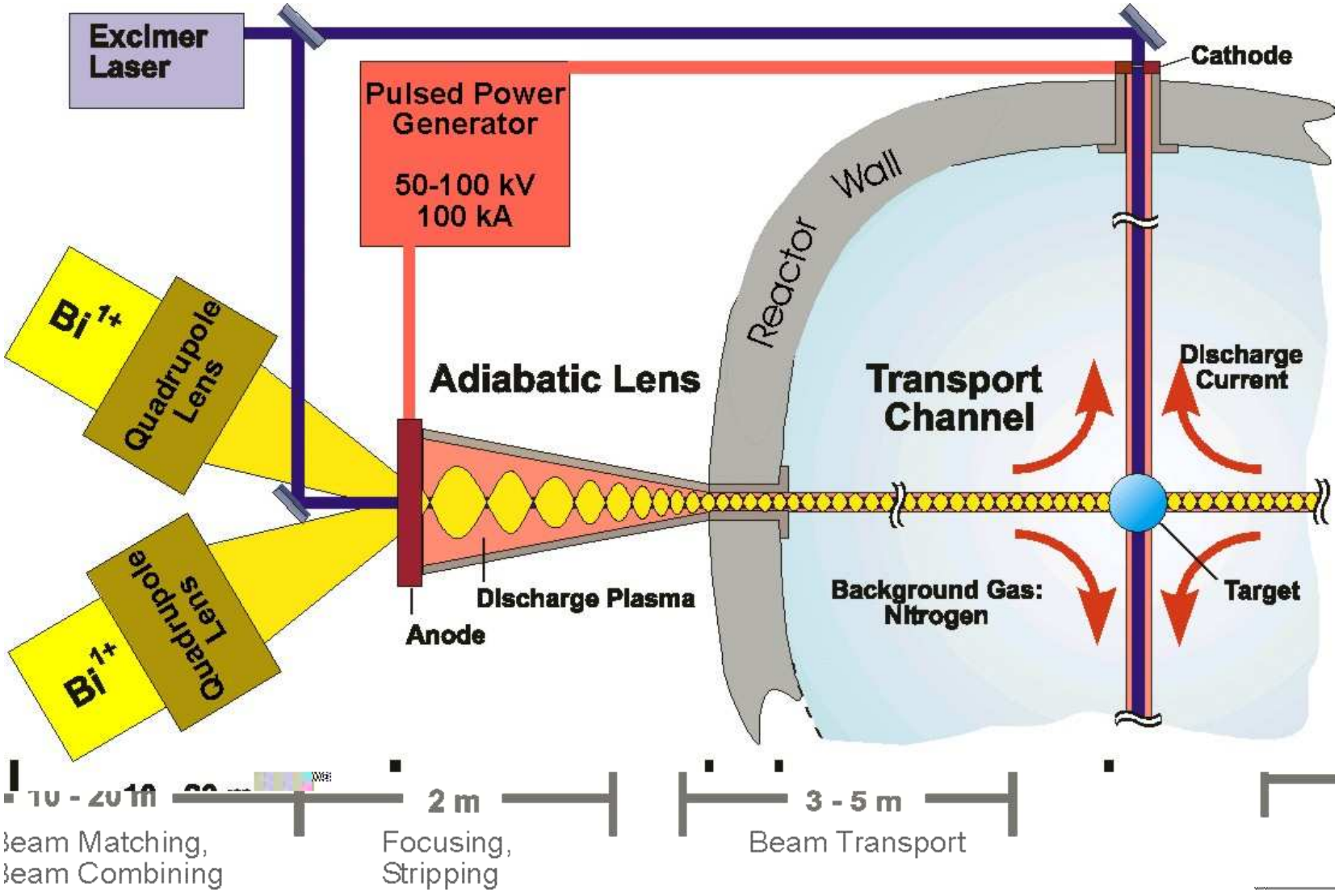
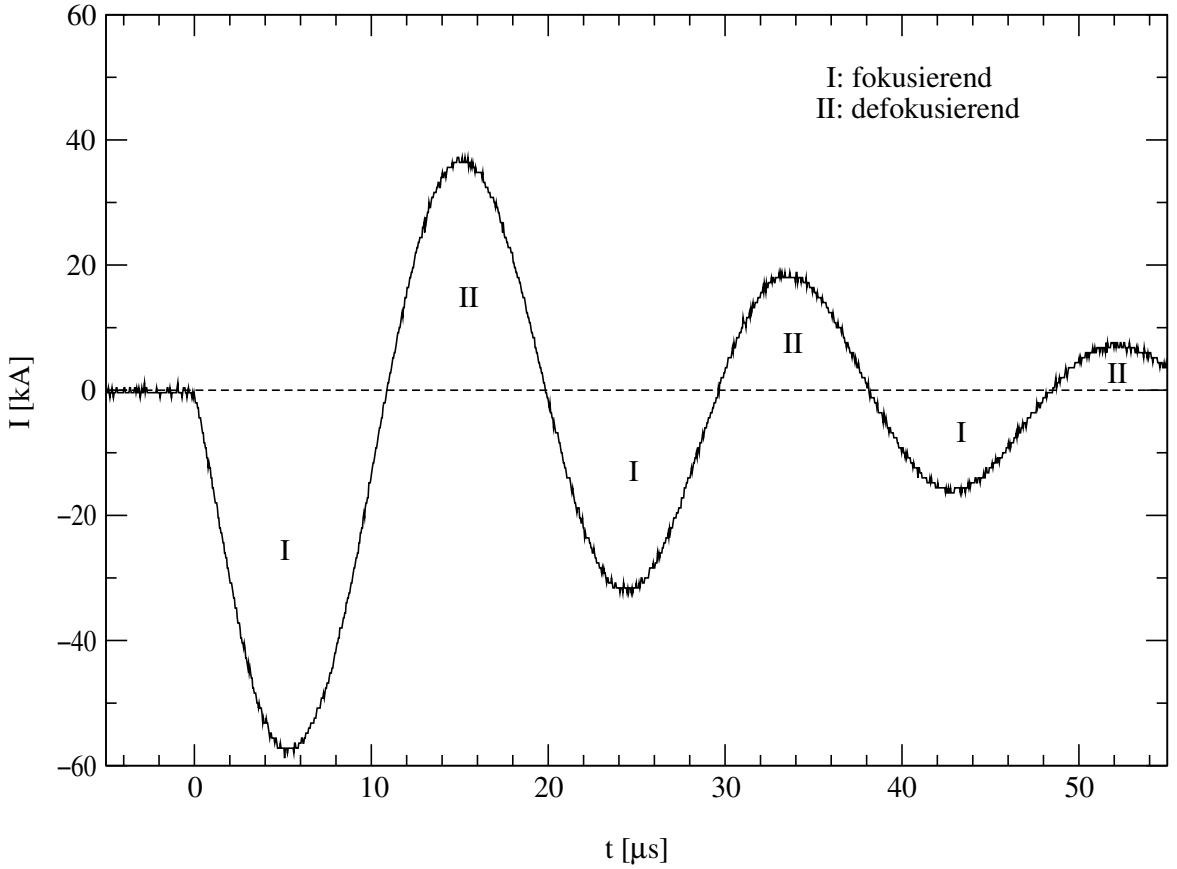
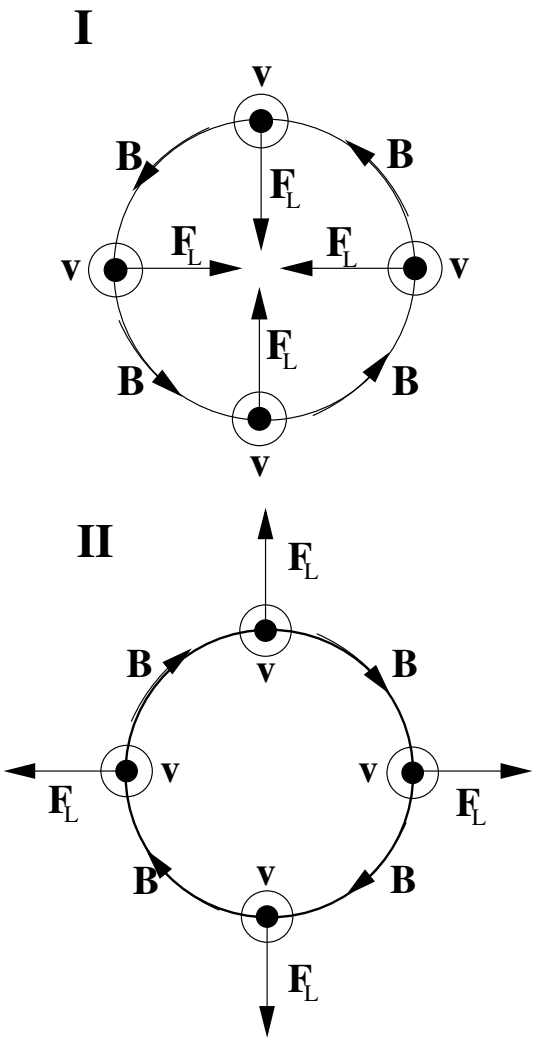
Reactor concept



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

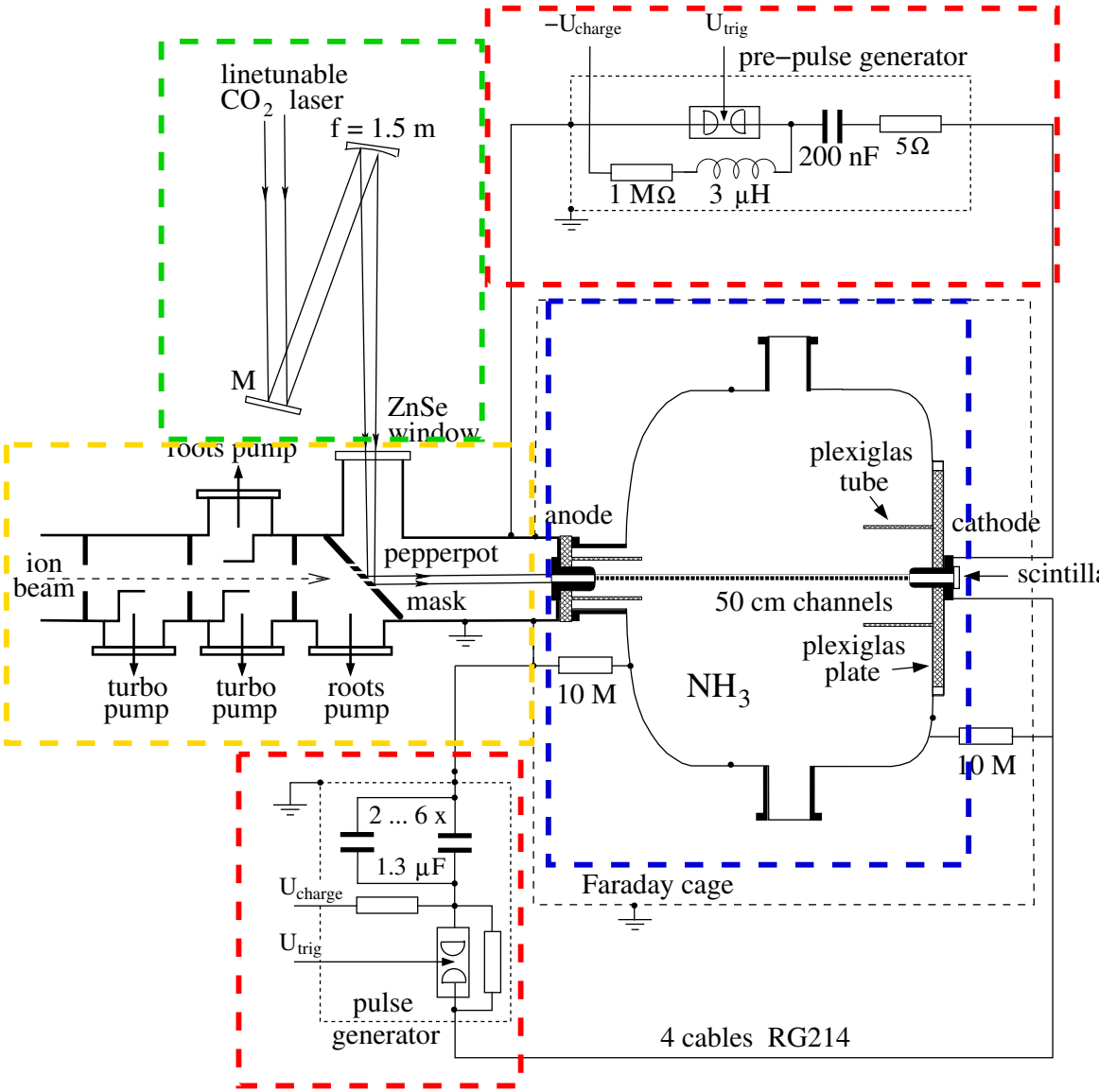
$$\rho \geq 3.8 \cdot 10^{-3}\ \text{kg/m}^3\ (0.5\,\text{Torr})$$

Experimental setup

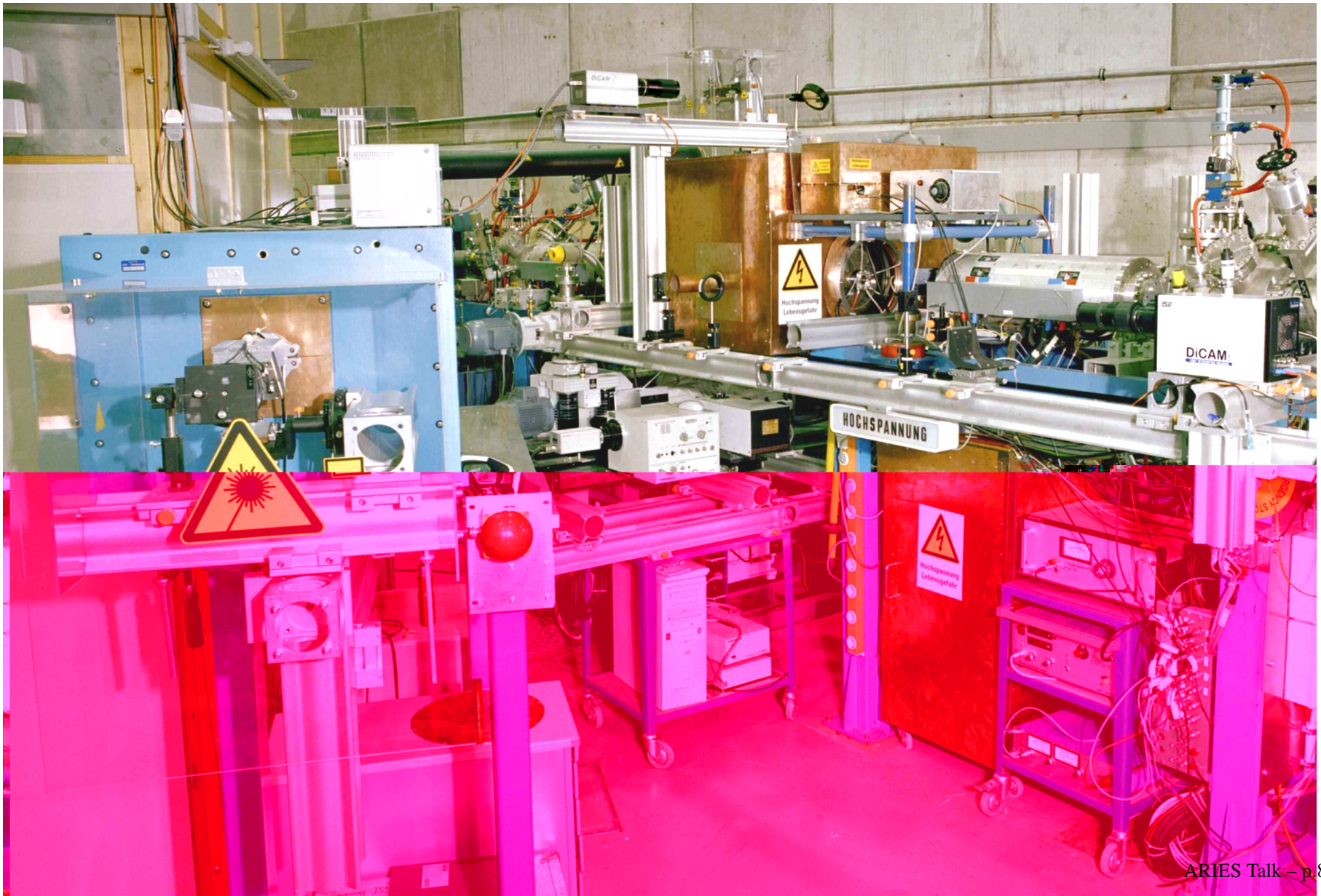
Main parts:

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

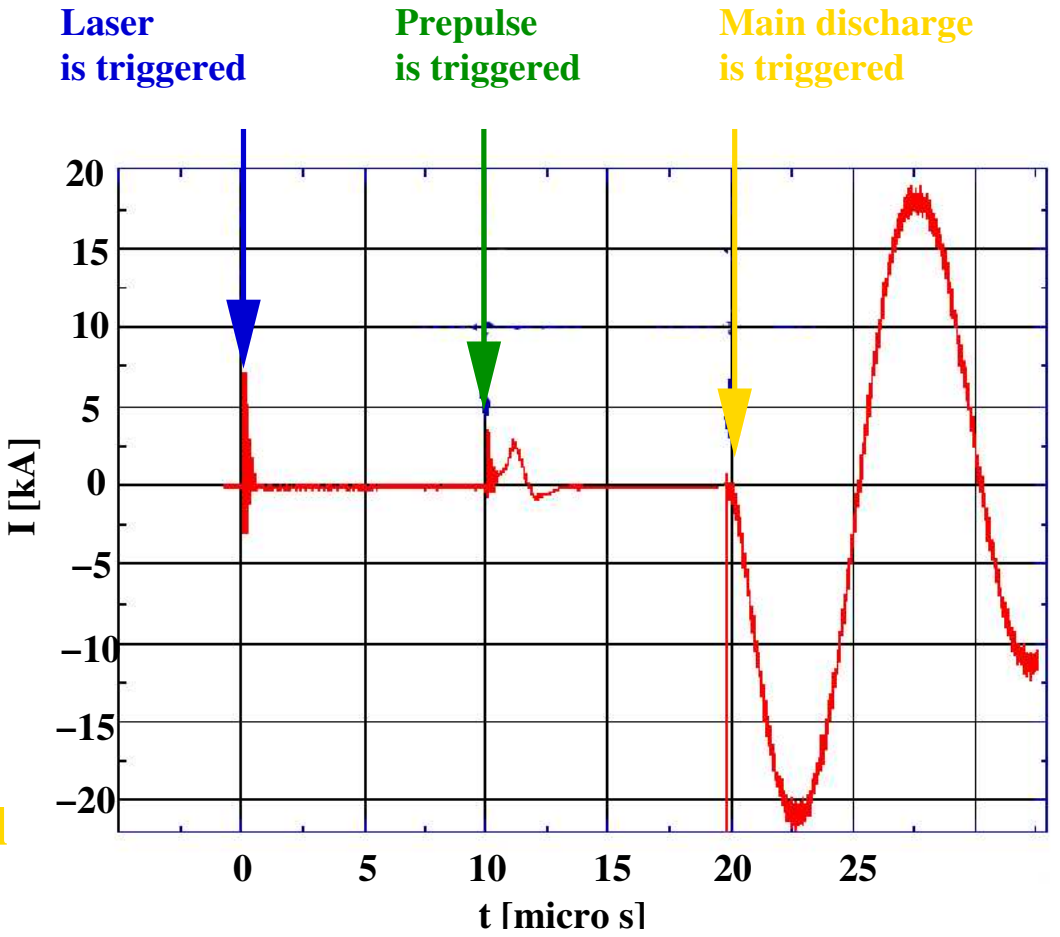
Channel creation

Three steps:

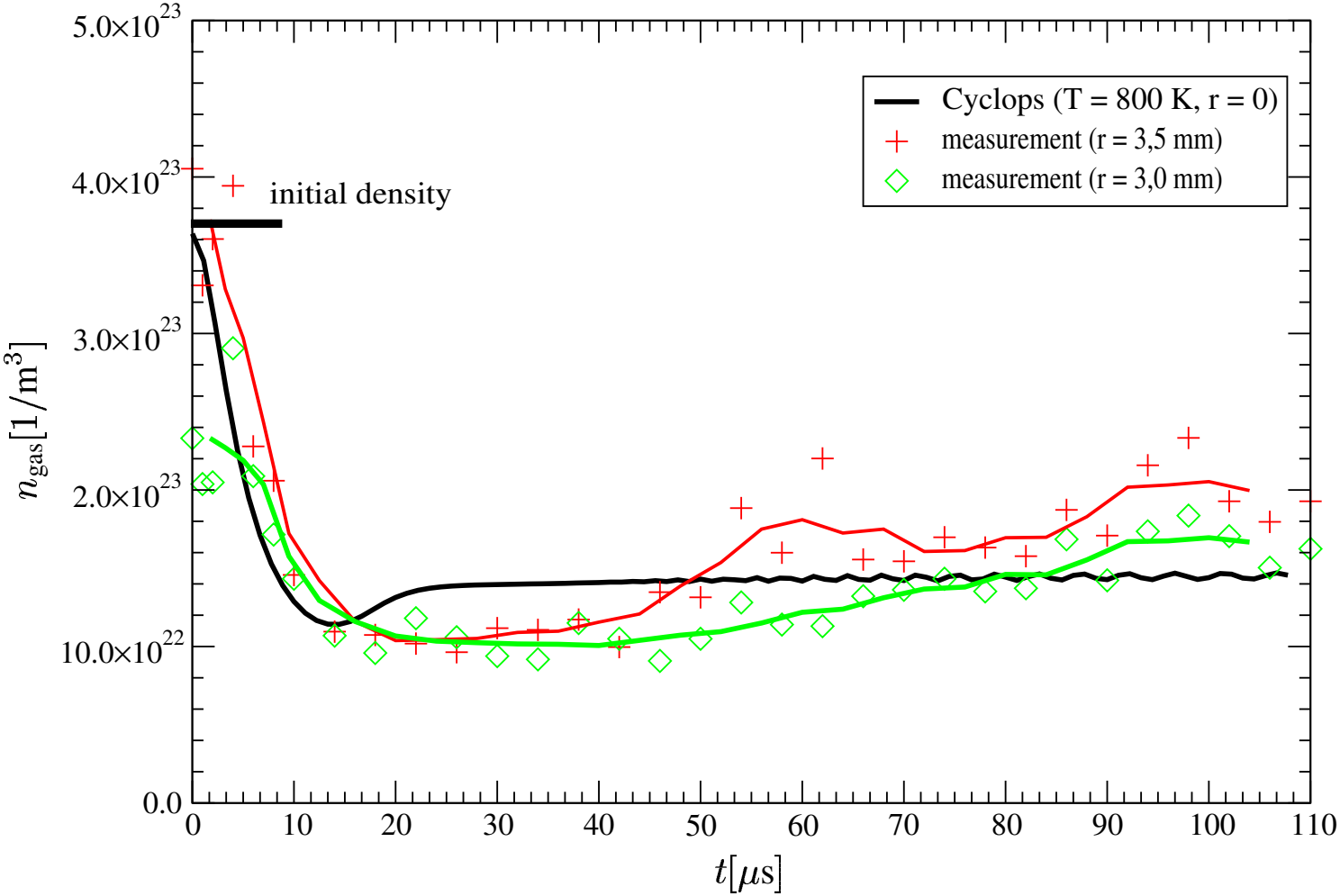
1) Laser:
Energy: 5 J
Heating leads to rarefaction on axis

2) Prepulse
Energy: 40 J
Further rarefaction, Ionization

3) Main discharge
Energy: 3 kJ
Create plasma channel



Laser - density on axis

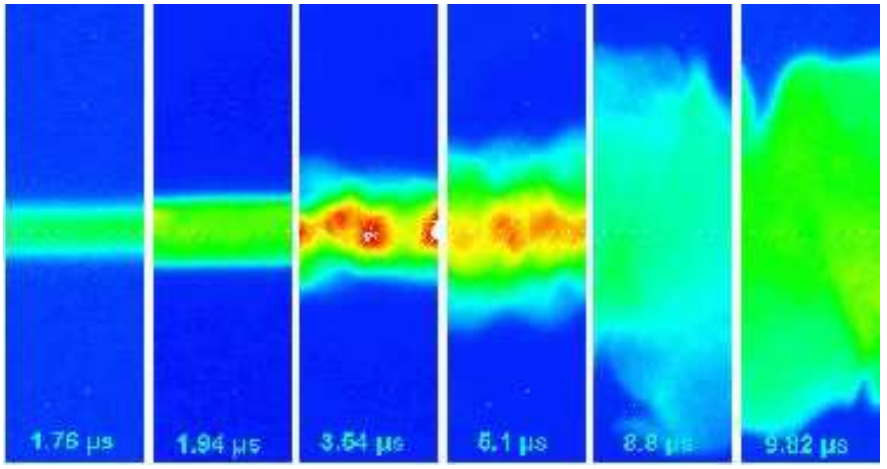


→ good agreement between simulation and measurement

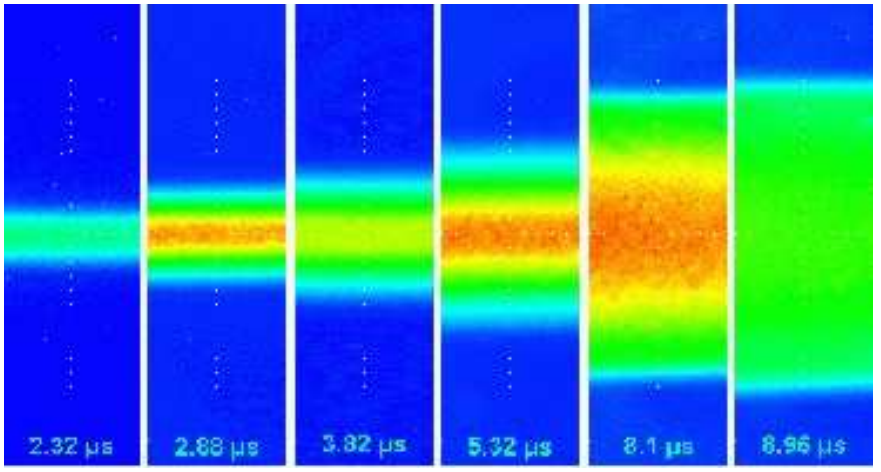
Prepulse

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

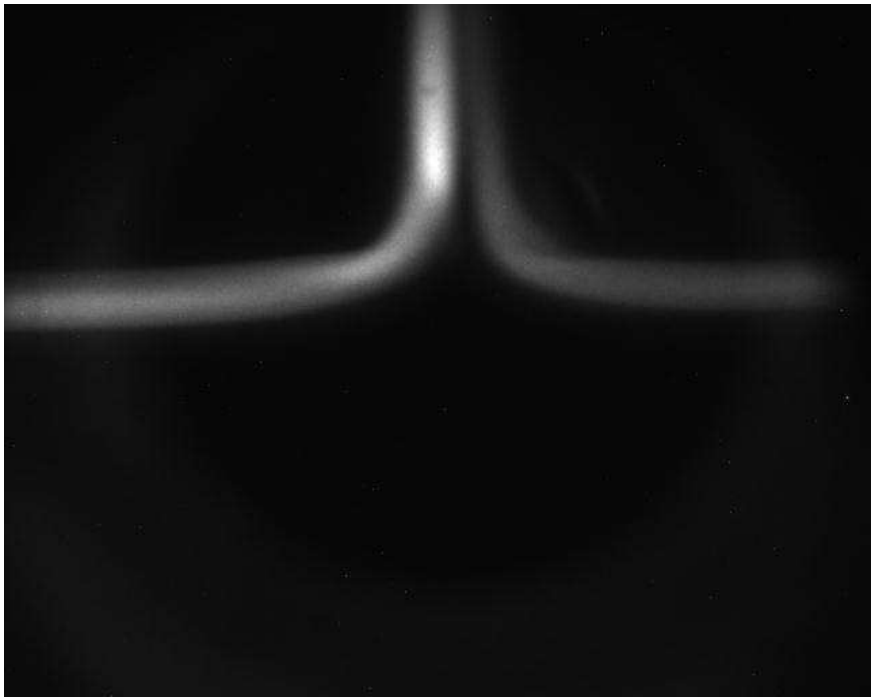


Growth rate for kink instability

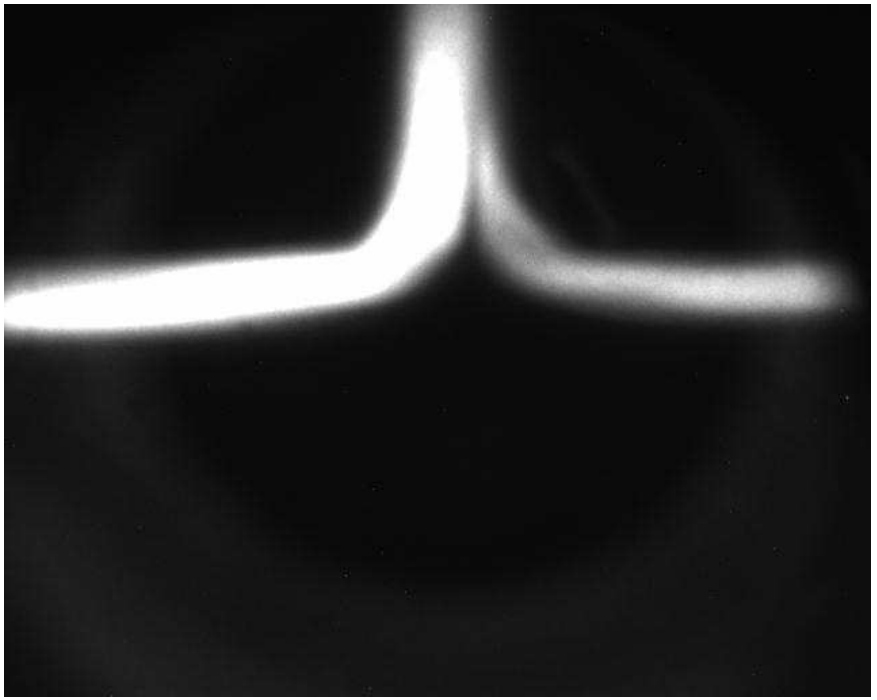
$$\Gamma_{\text{kink}} \propto \frac{B_\theta}{\sqrt{\rho_{\text{ch}}}} \left(\frac{\rho_{\text{ch}}}{\rho_{\text{g}}} \right)^{0.5}$$

Crossed channels

Beginning



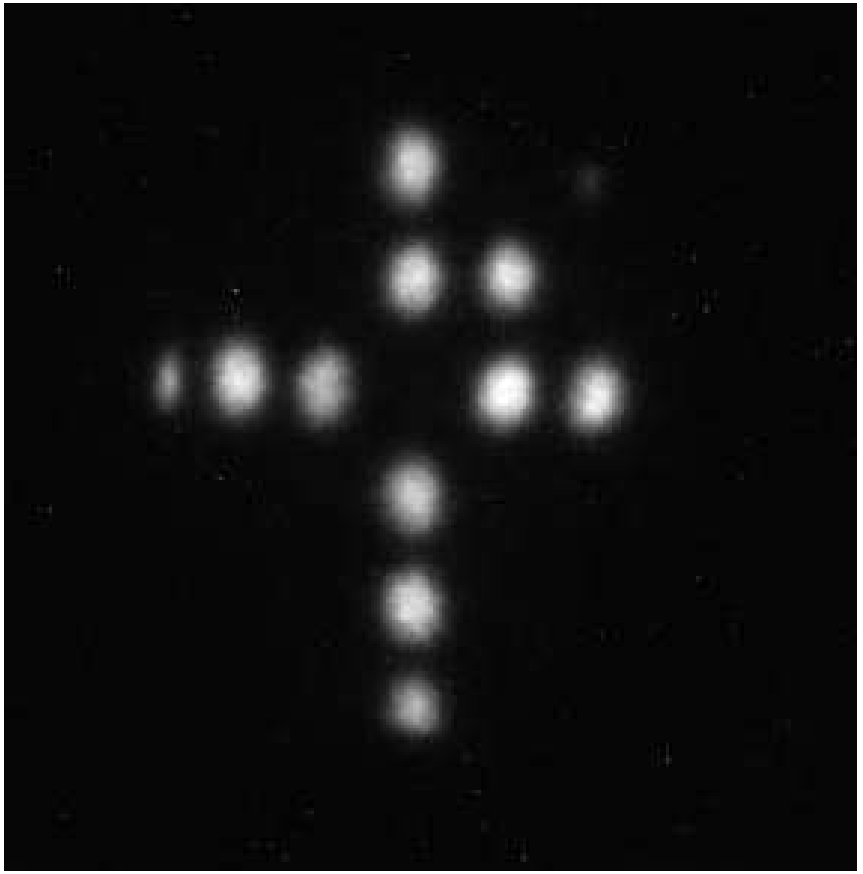
Current maximum



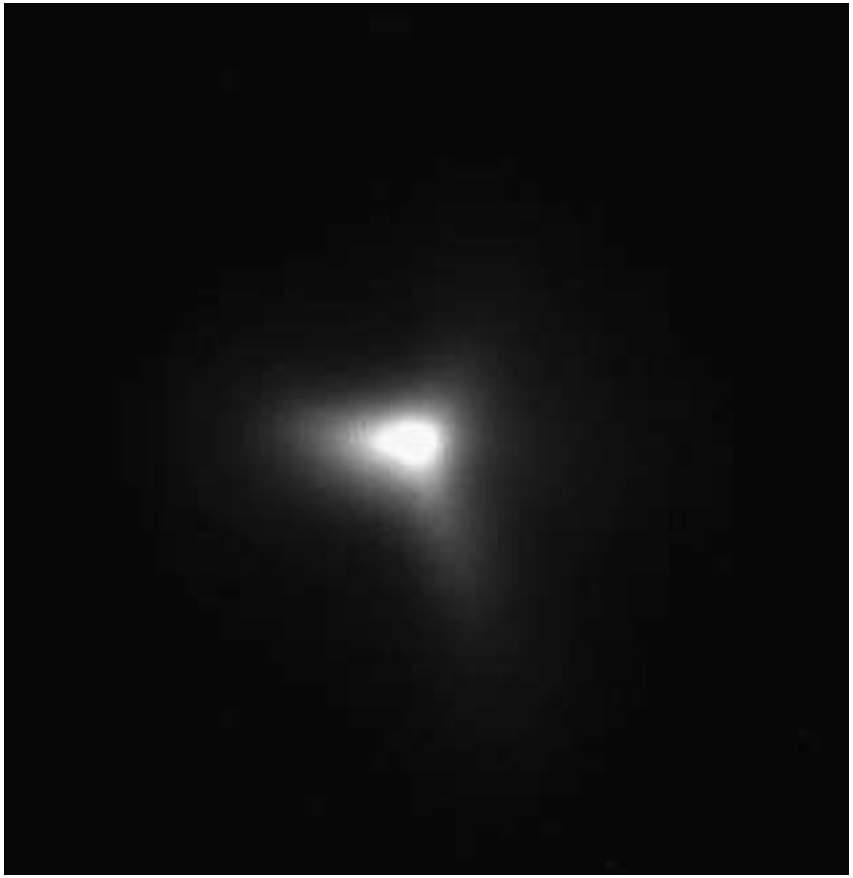
- discharge follows laser paths

Beam transport

Unfocused Beams

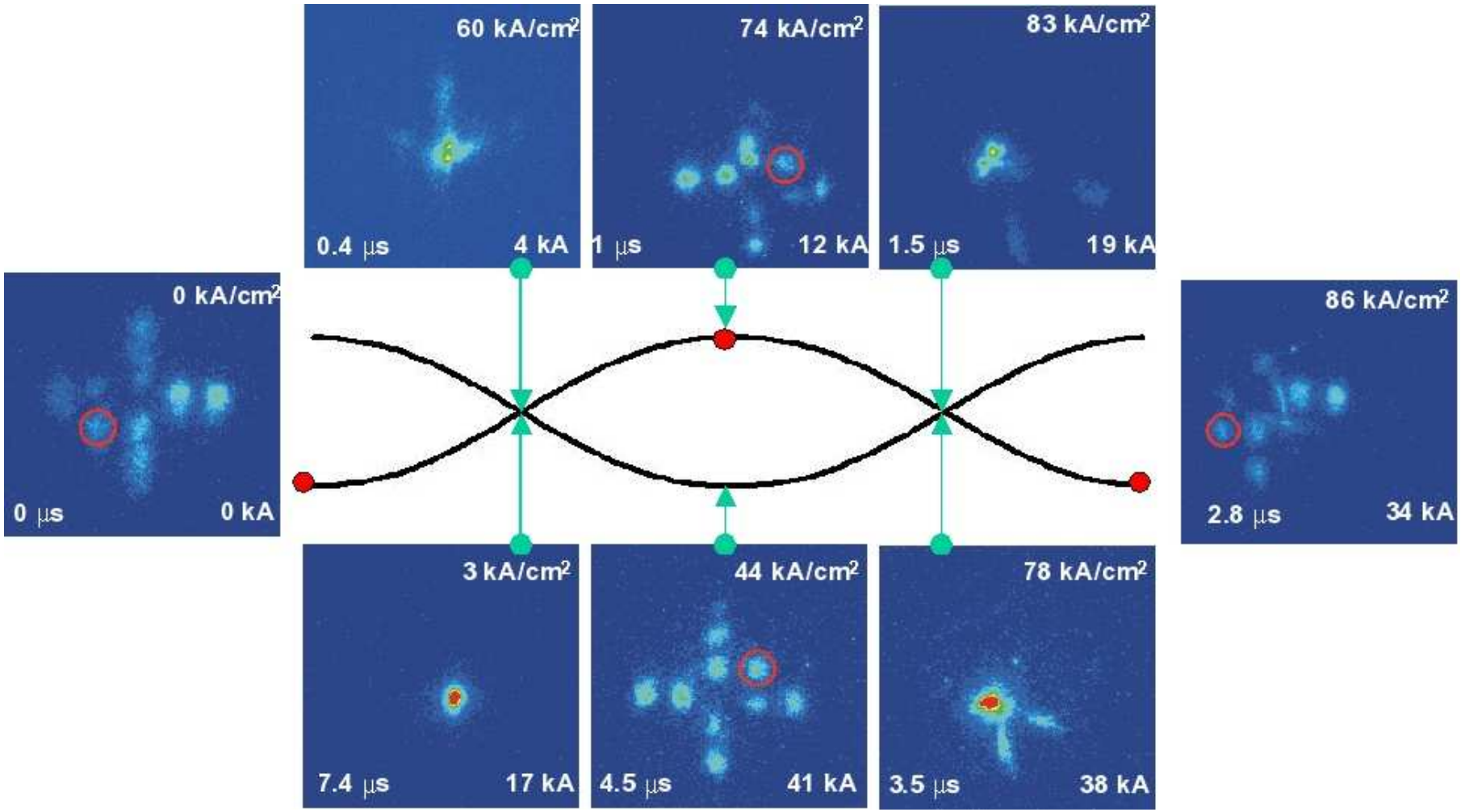


Focused Beams



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