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Activity of the PF-1000U laboratory
September 2013-September 2014

Marian Paduch, Ryszard Miklaszewski

Finannces:

Grant from the National Centre for Research and Developement ~ 80 kEuro (closed)

Support for Special Research Infrastructures ~ 90 kEuro

Three grants IAEA CRP (Coordinated Research Projects) ~ 150 kEuro

EURATOM grants ~ 20 kEuro

Support from Czech government ~ 20 kEuro

TOTAL ~ 360 kEuro

Eksperimental activity (September 2012 – September 2013)

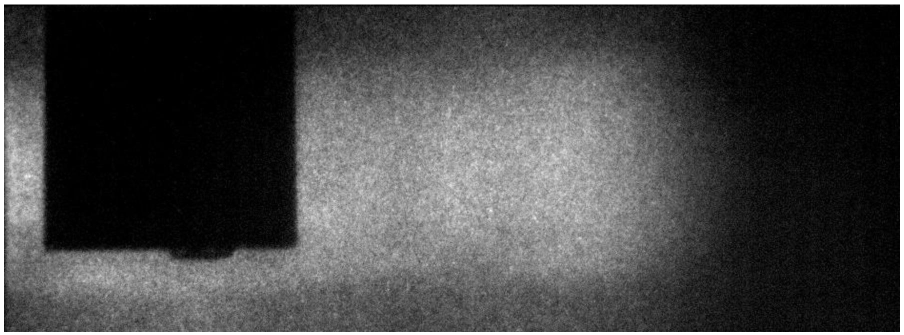
11 experimental sessions on PF-1000U (64 days, 540 discharges)

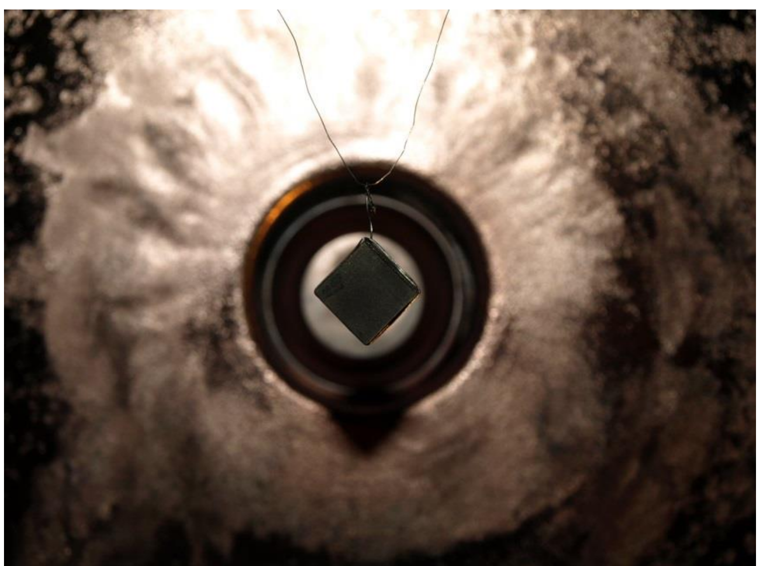
- **Including 3 x 2 weeks with participation of our Czech collegues from CVUT(Prague) – gas puffing**
- **30 days with participation of the NCBJ team under leadership of Dr. Sadowska**
- **Experiments with pendulum.**
- **Irradiation of samples for EURATOM (IPPLM, Warsaw Technical University, IPP Prague).**
- **Testing of various diagnostics.**

12 papers (*Plasma Phys. & Controlled Fusion, Phys. Plasmas, Physics Scripta, IEEE Trans.Plasma Phys., Plasma Phys. Rep.*)

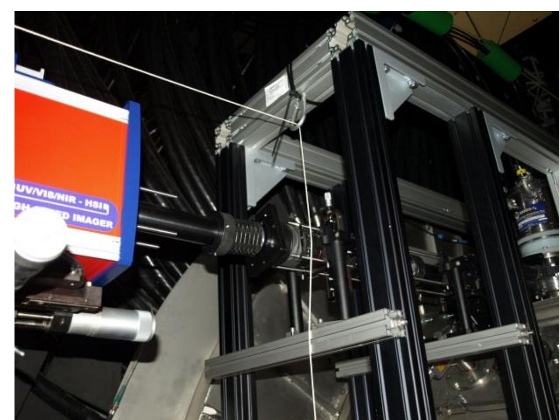
Education – active participation of PhD students from NCBJ and CVUT in experimental sessions. Three students from Warsaw University on placements (3

Measurement of plasma stream and fast ions energy deposition at a target using a pendulum





Side-on and front view of the pendulum



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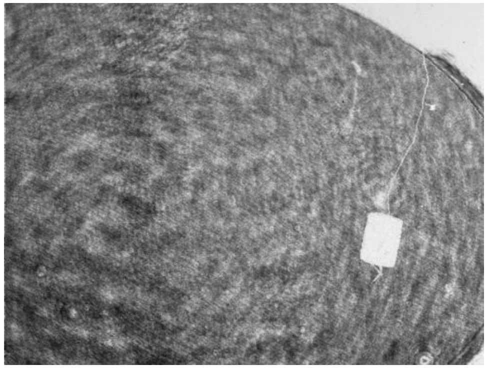

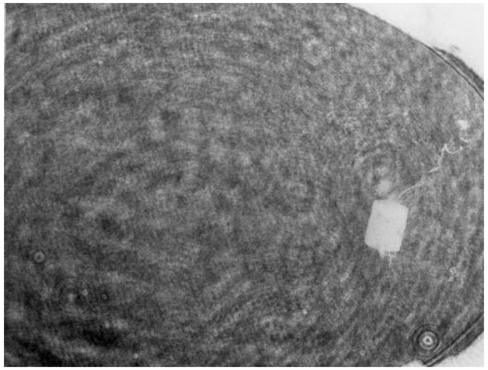

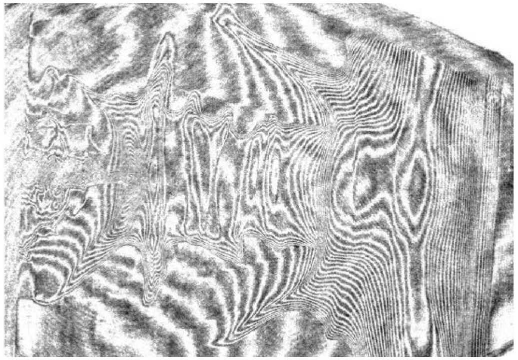

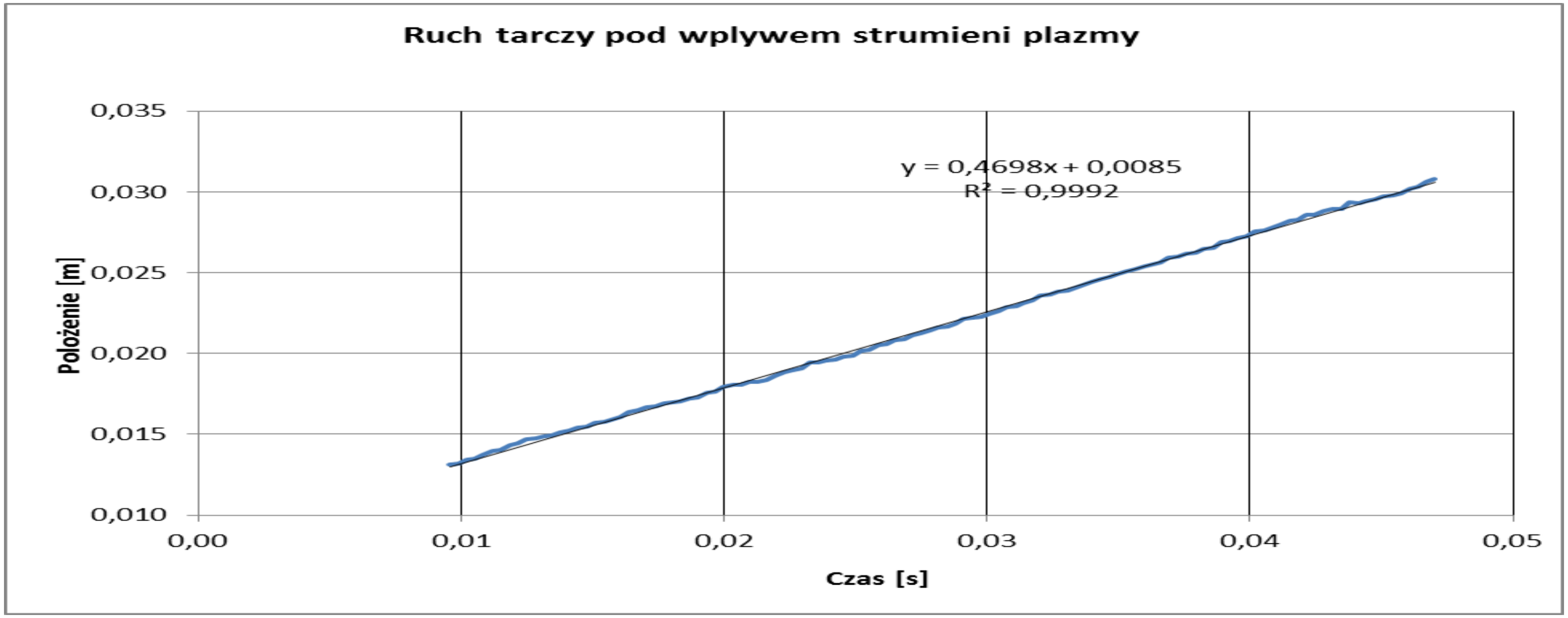

Results: charging voltage 19 kV - taget velocity 0.47 m/s

23 kV – target velocity 0,82 m/s

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Modification and testing of the gas injection system at the PF-1000U
First experiments

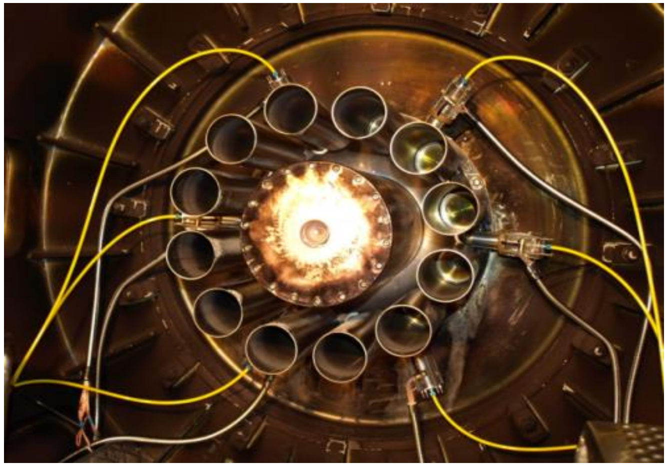
There is a possibility of getting additional “degrees of freedom” of the Plasma-Focus operation by special gas injecting system.

Such a system has been manufactured , installed and tested.

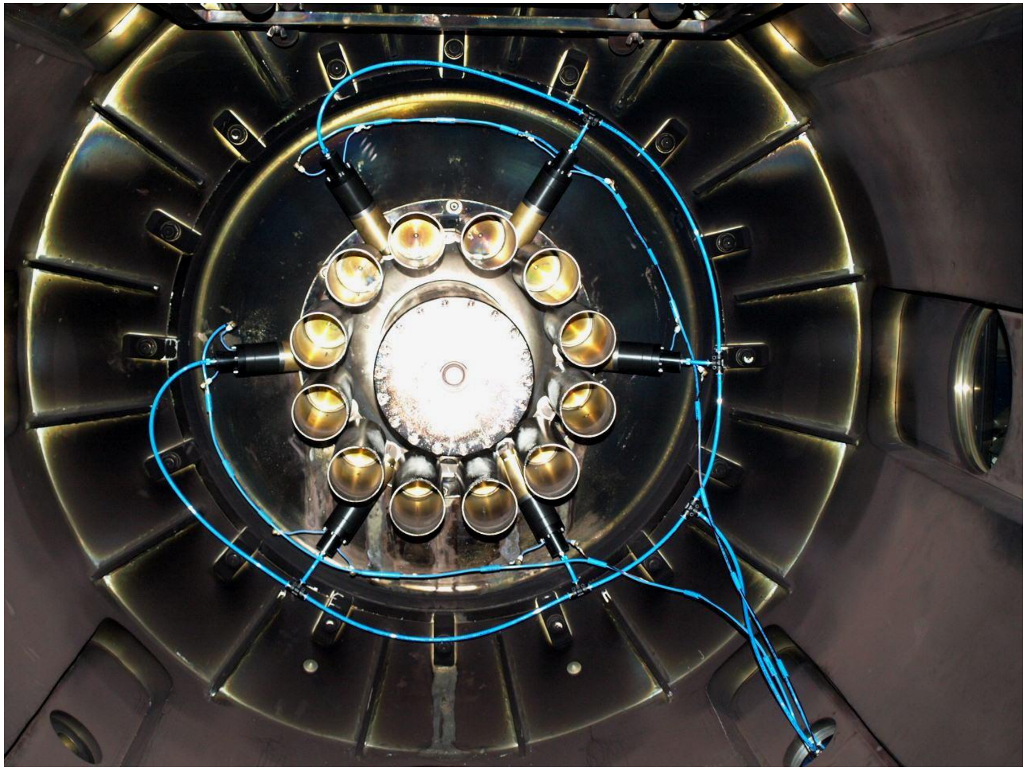
It was found that basic elements of the system – the injectors -were not working properly and and have been replaced.

The new version – designed and manufactured by our Czech collegues from CVUT proved to be very good.

Results of experiments – presentation of Prof. Kubes



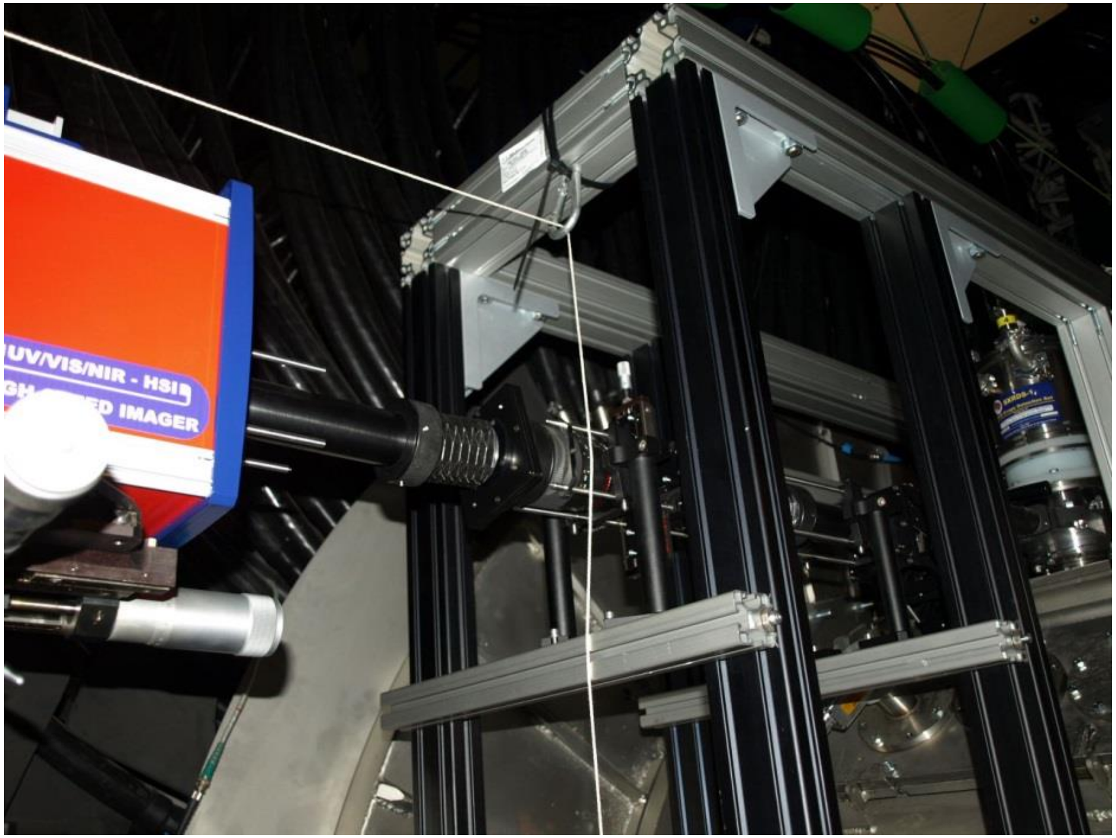
Old system



New injectors

New diagnostics:

Electro-optical High Speed Imager



Visible range
Frame duration - 3 ns
1 frame/μs
2048x2048 piksels

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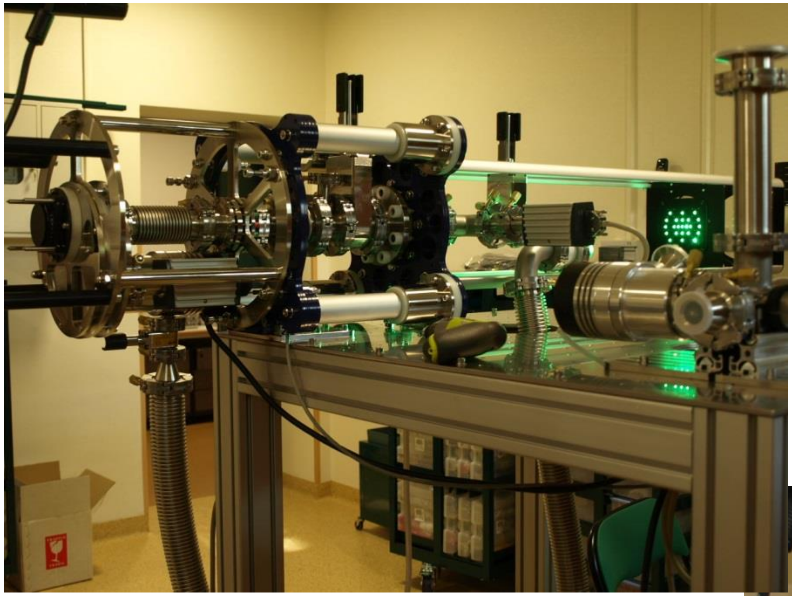
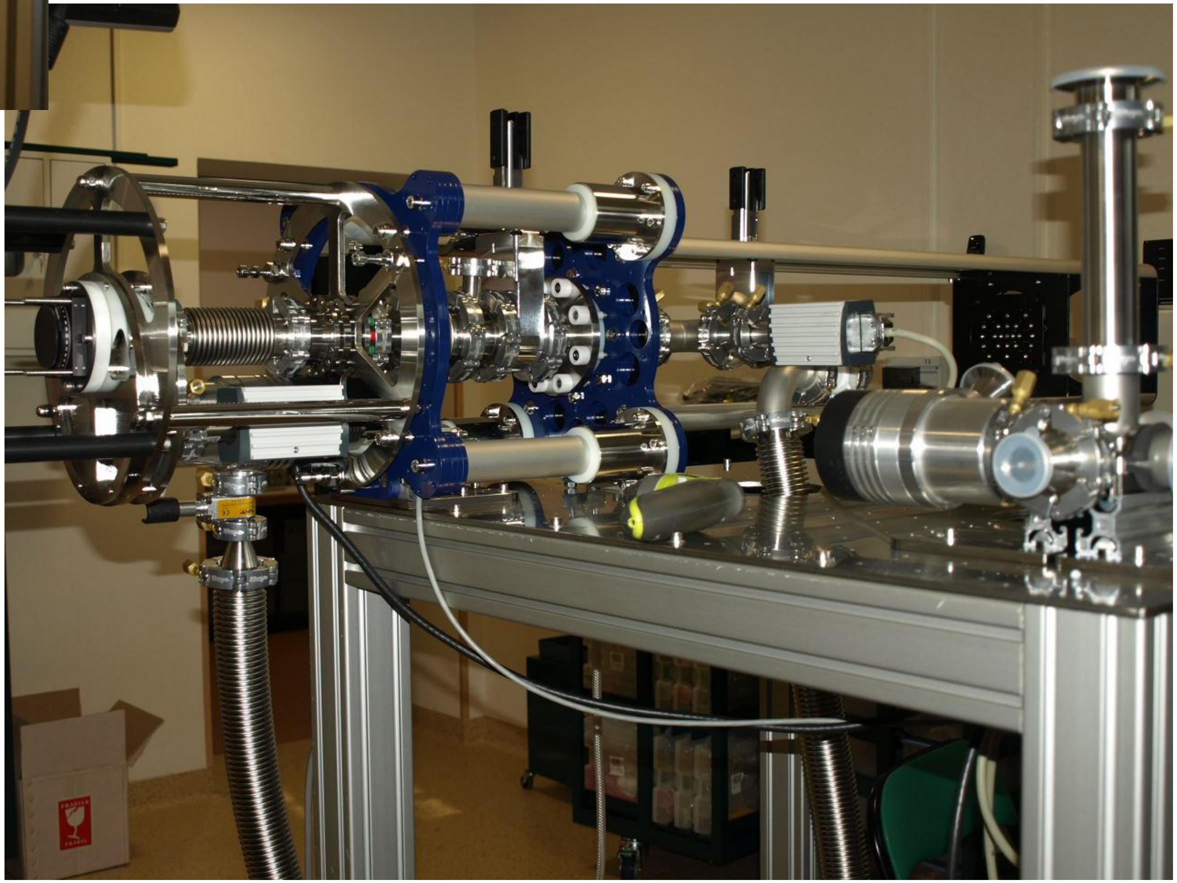


New version of the four-frame camera (4 sectors MCP)

frame duration -1.8 ns
delay between frames 0-20 ns



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Frame camera for medium and hard X-ray pictures

frame duration ~3 ns

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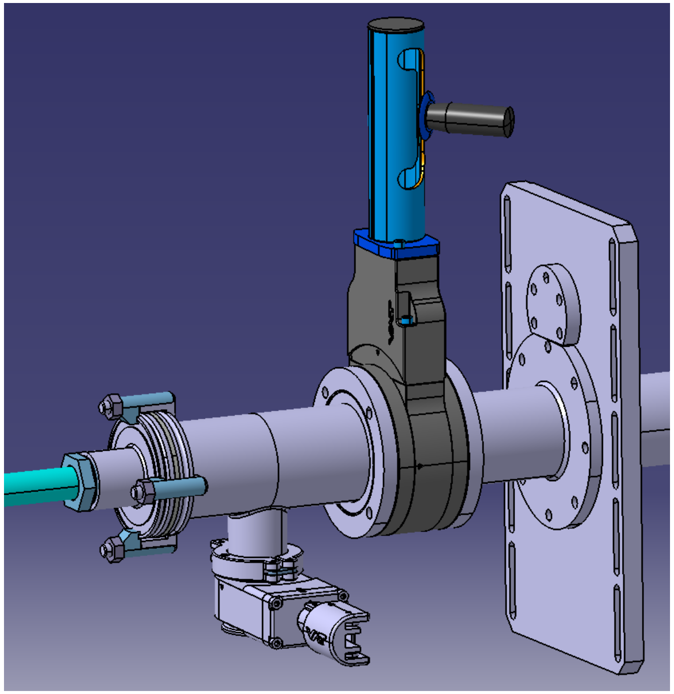
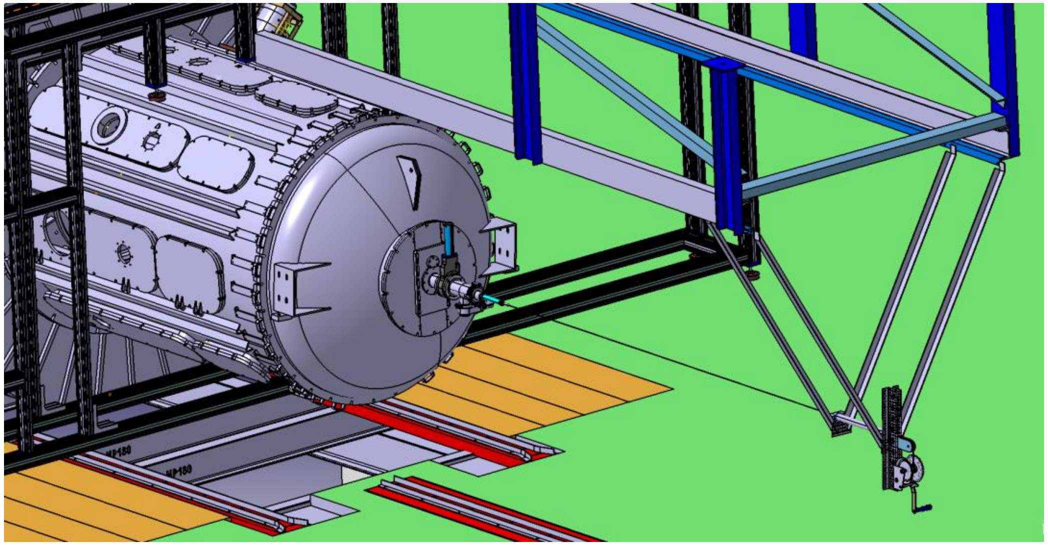
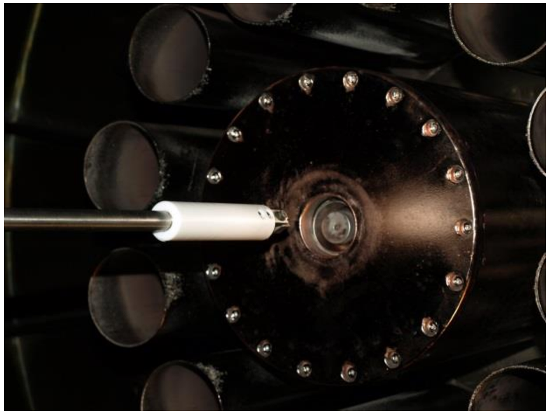
New system that allows to place targets in front of the pinch. (without getting air in)

Target dimennsions – up to 55 mm



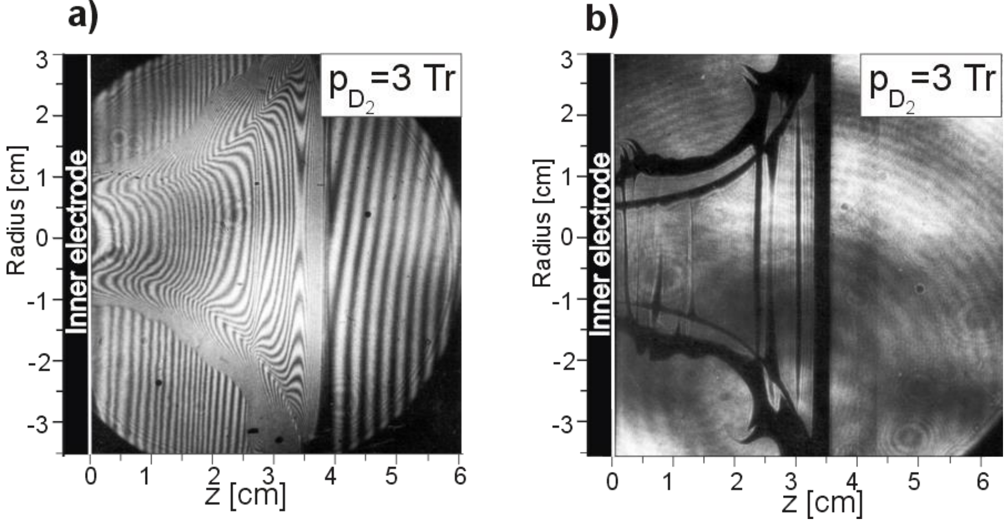




Plans for future:

- Investigation of radiative collapse (Prof. Kunze).
- Laboratory astrophysics – investigation of plasma jets - within the frame of a project leaded by Dr. Krauz.
- Furher exploration of opportunities given by the gas-puff system.
- Materials' investigation.
- Re-calibration of the neutron diagnostics.


Thank you for attention



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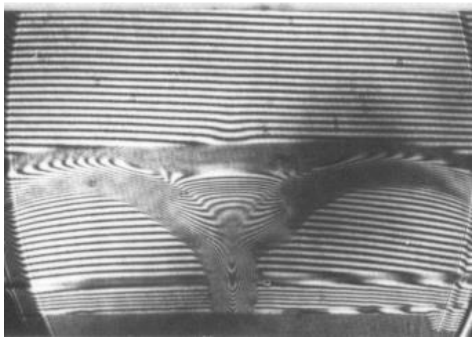
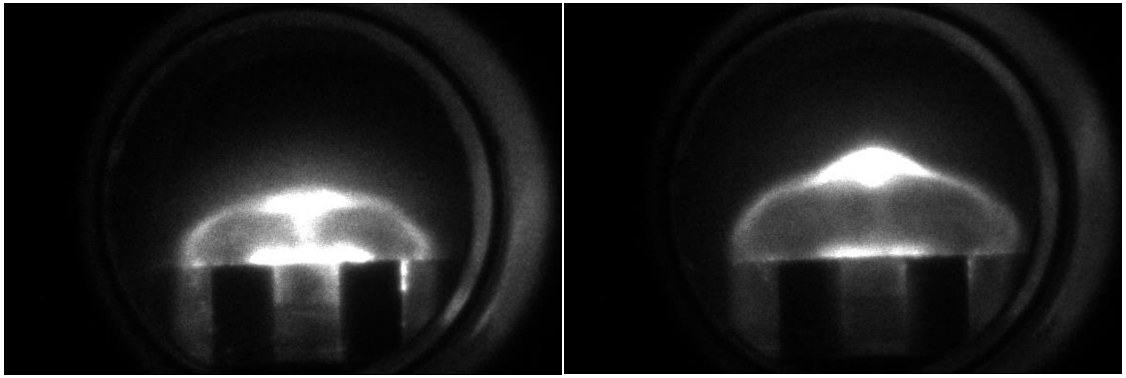
PF-360 (120 kJ, Poland)

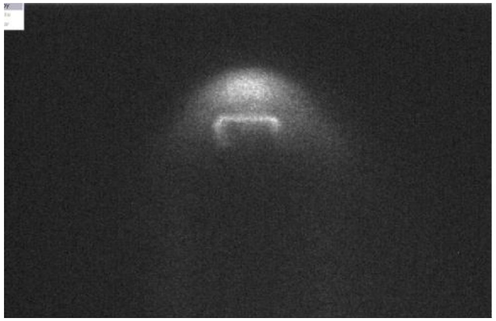
Scalability!



PF-150 (60 kJ, Poland)



50 J (Argentina)



100 mJ (Argentina)

L.Sotto

Plasma Sources Sci. Technol. 19 (2010) 055017
(velocity, temperature=const.)

Plan of the talk:

1/ Similarities within the ideal MHD

2/ Non –ideal MHD

3/ Consequences of the constant driving factor

4/ Some scaling properties of the electric circuit

5/ Snow-plow-slug model

Equations of the ideal MHD

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0$$

continuity

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \cdot \vec{v}\right) = -\nabla p - \frac{1}{c}\vec{j} \times \vec{B}$$

motion

$$\frac{\partial p}{\partial t} + \vec{v} \cdot \nabla p = -\gamma p \nabla \cdot \vec{v}$$

energy

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \vec{v} \times \vec{B}$$

B- field

$$p = nkT$$

eq. of state

Dimension basis

I_0 – maximum current
R_0 – radius of the central electrode
n_0 – concentration of the filing gas

$$B_0 = \frac{2I_0}{cR_0} \qquad p_0 = \frac{B_0^2}{4\pi} \qquad v_0^2 = \frac{p_0}{\rho_0}$$

$$t_0 = \frac{R_0}{v_0} \qquad T_0 = \frac{p_0}{n_0} \qquad \rho_0 = Mn_0$$

The set of ideal MD equations is invariant under the following transformation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0$$

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \cdot \vec{v}\right) = -\nabla p - \frac{1}{c}\vec{j} \times \vec{B}$$

$$\frac{\partial p}{\partial t} + \vec{v} \cdot \nabla p = -\gamma p \nabla \vec{v}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \vec{v} \times \vec{B}$$

$$p = nkT$$

$$r = R_0 r'$$

$$t = t_0 t'$$

$$n = n_0 n'$$

$$\vec{v} = v_0 \vec{v}'$$

$$T = T_0 T'$$

$$p = p_0 p'$$

$$\vec{B} = B_0 \vec{B}'$$

$$\frac{\partial \rho'}{\partial t'} + \nabla \cdot \rho' \vec{v}' = 0$$

$$\rho'\left(\frac{\partial \vec{v}'}{\partial t'} + \vec{v}' \cdot \nabla \cdot \vec{v}'\right) = -\nabla p' - \frac{1}{c}\vec{j}' \times \vec{B}'$$

$$\frac{\partial p'}{\partial t'} + \vec{v}' \cdot \nabla p' = -\gamma p' \nabla \vec{v}'$$

$$\frac{\partial \vec{B}'}{\partial t'} = \nabla \times \vec{v}' \times \vec{B}'$$

$$p' = n' k T'$$

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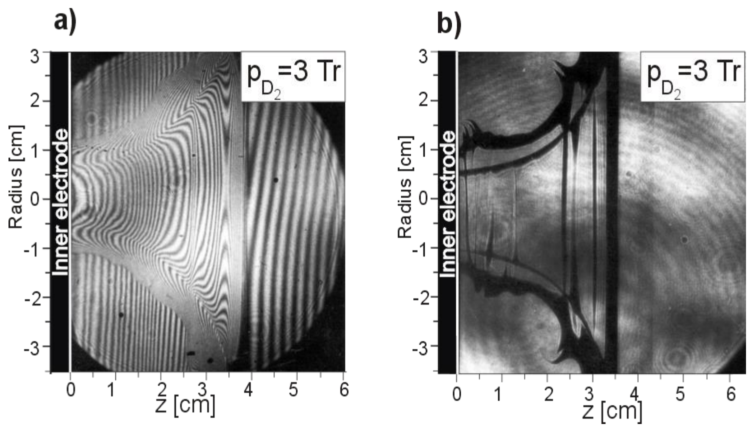


The question is, if the ideal MHD model is a sufficient tool to describe dynamics of the PF plasma , at least in the run down, collapse and, eventually, the pinch formation phase.

Concerning the run-down and collapse phase the answer seems to be positive as even much simpler model, so called snow plow model (its 2D version), that is something like 0-dimensional ideal MHD model, proved to be capable to describe the plasma sheath shape and dynamics with good accuracy.

A well developed plasma sheath is a strong, non-cylindrical shock wave driven by a magnetic piston propagating in the filing gas.

Basic parameters of plasma in the shock wave can be obtained from the theory that takes into account only hyperbolic (dissipation-less) part of the HD or MHD equations [Zeldovich, Witham] as a so called weak solution.

Dissipative processes like viscosity and thermal conductivity determines the width of the transition zone (width of the shock front) between pre- and post- shock plasma.

The second question is if the three basic dimensional parameters assumed above (I_0 – maximum current, R_0 – radius of the central electrode, n_0 – concentration of the gas filing a chamber) can be treated as being the unique ones (for the problem we are dealing with).

In the case of "I_0" the answer is positive provided the current can be treated as being almost constant (the current deep is not high). This assumption is quite well justified for small PF devices with relatively high value of the relation between inductances $(L_0+L_p)/L_0$.

Analyzing the case of "R_0" one may be worried about the radius of the outer electrode and ask if it has any influence on the plasma sheath propagation? The answer seems to be negative at least once we deal with some idealized picture of the phenomena.

From the theory of strong shock waves [Zeldowicz] the sound velocity in the sheath is of the same order of magnitude as the sheath velocity and signals from the outer electrode should not influence the leading front of the sheath near the central electrode surface in both run-down as well as collapse phases.

Any solution (set of plasma parameters) describing dynamics of the plasma and taken from numerical modeling or exsperimnet can be than rescaled to new conditions using the transformation described above.

Non-ideal MHD

Diachenko, Imshennik -1967
Imshennik, 1972

$$\alpha = \frac{p_0^2}{\rho_0^3 R_0} \qquad \beta = \rho_0 R_0^2$$

It can be shown that

$$\alpha \approx \frac{\lambda}{R_0} \qquad \beta \approx \frac{R_0^2}{r_c^2}$$

Where: λ - is a mean free path and r_c - is the gyro-radius.

$$\frac{3}{2} n \frac{d_e T_e}{dt} + \nabla \cdot \left[\begin{array}{l} C'_{qu} \dfrac{n^2}{B T_e^{1/2}} \left(\vec{h} \times \vec{u}\right) \left[\dfrac{1}{\sqrt{\alpha^2 \beta}} \right] - C'_{qt} \dfrac{n^2}{B^2 T_e^{1/2}} \nabla T_e \left[\dfrac{1}{\alpha \beta} \right] - \\ - C'_{qh} \dfrac{n T_e}{B} \left(\vec{h} \times \nabla T_e\right) \left[\dfrac{1}{\sqrt{\beta}} \right] \end{array} \right] + \ldots = 0$$

$$\alpha, \frac{1}{\sqrt{\beta}}, \frac{1}{\alpha \beta}, \frac{1}{\sqrt{\alpha^2 \beta}}$$

$$\alpha = \frac{p_0^2}{R_0 \rho_0^3} \qquad \beta = R_0^2 \rho_0 \qquad \frac{I_0}{R_0 \sqrt{\rho_0}} = const \quad \Rightarrow$$

$$==> \quad \alpha \sim \frac{1}{R_0 \rho_0} \sim \frac{1}{\sqrt{\rho_0} I_0} \qquad \beta \approx I_0^2$$

$$\alpha \approx \frac{\lambda}{R_0} << 1 \qquad \frac{1}{\beta} \approx \frac{r_c^2}{R_0^2} << 1$$

Conditions for validity of the MHD model with transport

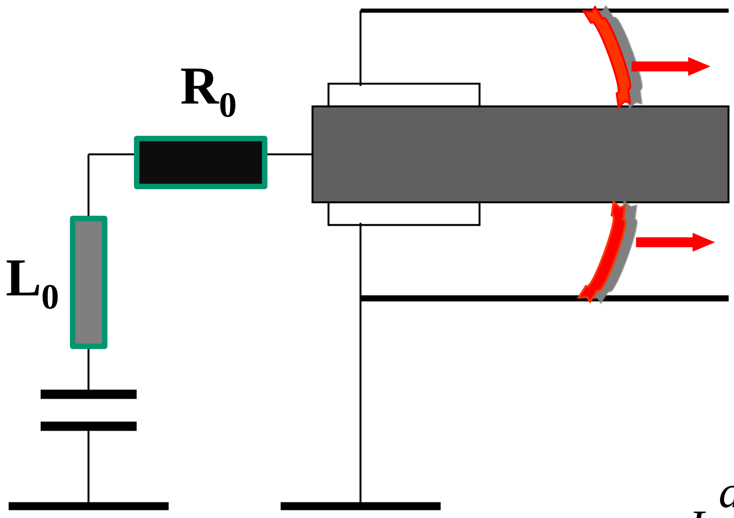
If current $\nearrow$ $\quad \alpha, \frac{1}{\beta}$ $\searrow$

If current ↗

$$\alpha \sim \frac{1}{\sqrt{\rho_0} I_0} \quad \frac{1}{\beta} \sim \frac{1}{I_0^2} \quad \frac{1}{\alpha\beta} \sim \frac{\sqrt{\rho_0}}{I_0}, \quad \frac{1}{\sqrt{\alpha^2\beta}} \sim \sqrt{\rho_0}$$ ↘

The same with anomalous collision frequency of the lower-hybrid instability responsible for enchancement of the plasma resistivity.

$$v_{eff} = \left(\frac{u}{v_{Ti}}\right)^2 \sqrt{\omega_e \omega_i} \cong \frac{\sqrt{\rho_0}}{I_0^2}$$



Some scaling properties of the PF electric circuit

$$I\frac{dL_p}{dt}+\left(L_0+L_p\right)\frac{dI}{dt}+R_\Omega I=U_0-\int_0^t\frac{I}{C}dt'$$

$$\frac{dI}{dt}=\frac{\left(U_0-\int_0^t\frac{I}{C}dt'\right)-R_\Omega I-I\frac{dL_p}{dt}}{\left(L_0+L_p\right)}$$

$$L_p=2Z_p\ln\frac{R_{out}}{R_{in}}$$

$$\frac{dL_p}{dt}=2\frac{dZ_p}{dt}\ln\frac{R_{out}}{R_{in}}=2v_p\ln\frac{R_{out}}{R_{in}}$$

$$\frac{dI}{dt}=\frac{\left(U_0-\int_0^t\frac{I}{C}dt'\right)-R_\Omega I-2v_pI\ln\frac{R_{out}}{R_{in}}}{\left(L_0+L_p\right)}$$

$$\frac{dI}{dt}=\frac{\left(U_0-\int_0^t \frac{I}{C}dt'\right)-R_\Omega I-2v_p I\ln\frac{R_{out}}{R_{in}}}{\left(L_0+L_p\right)}$$

Increasing current with the constrain of constant velocity:

Case I $\ln\frac{R_{out}}{R_{in}}=const$

Case II $\Delta R=const.$ $R_{out}=R_{in}+\Delta R$

$$\left[\left(U_0-\int_0^t \frac{I}{C}dt'\right)-R_\Omega I\right]-2Iv_p\ln\frac{R_{out}}{R_{in}}=0$$

$$\ln\frac{R_{in}+\Delta R}{R_{in}}=\ln\left(1+\frac{\Delta R}{R_{in}}\right)\sim\frac{\Delta R}{R_{in}}+\frac{1}{2}\left(\frac{\Delta R}{R_{in}}\right)^2$$

$$v_p\cong v_A\cong\frac{B}{\sqrt{\rho_0}}\cong\frac{I}{R_0\sqrt{\rho_0}}$$

$$I_{\max}<\frac{\left[\left(U_0-\int_0^t \frac{I}{C}dt'\right)-R_\Omega I\right]}{v_p\ln\frac{R_{out}}{R_{in}}}$$

$$\frac{dI}{dt}=\frac{\left[\left(U_0-\int_0^t \frac{I}{C}dt'\right)-R_\Omega I\right]-Iv_p\frac{\Delta R}{R_{in}}}{\left(L_0+L_p\right)}=\frac{\left[\left(U_0-\int_0^t \frac{I}{C}dt'\right)-R_\Omega I\right]-\sqrt{\rho_0}v_p^2\Delta R}{\left(L_0+L_p\right)}$$

Current saturation (S.Lee)!

Simple models of palsma sheath dynamics

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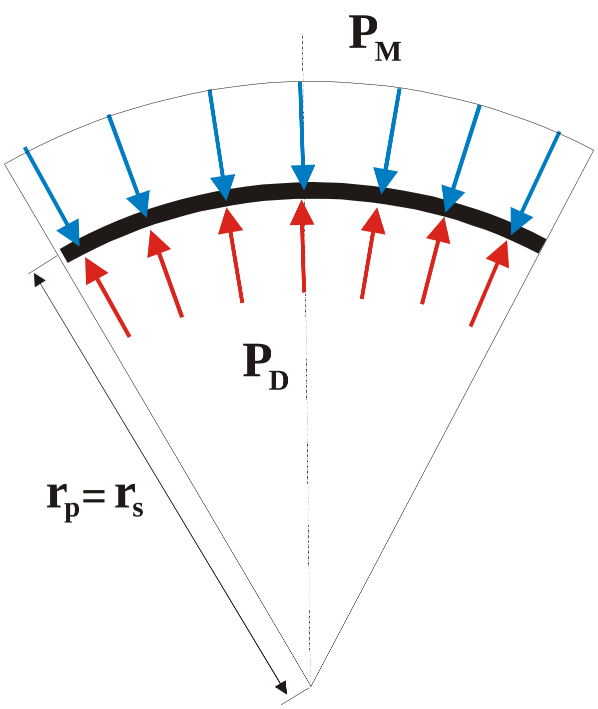
$$P_M = \frac{B^2}{8\pi} \quad \textit{– magnetic pressure}$$

$$P_D = \rho_0 v^2 \quad \textit{– dynamic pressure}$$

$$r_p \quad \textit{– outer radius of the pinch}$$

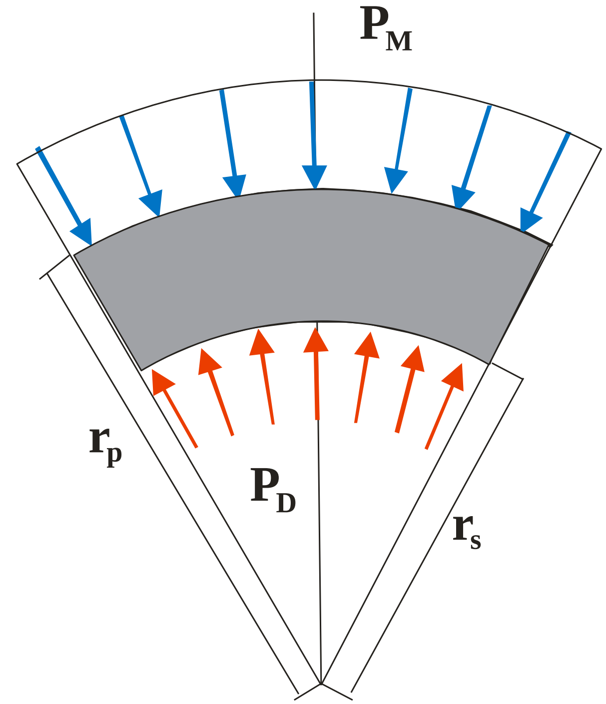
$$r_s \quad \textit{– radius of the shock wave}$$

Snow-plow



- infinitisimal width of the sheath
- P_M and P_D act on the same surface

Slug



- gives witdth of the sheath
- pressure obeys adiabatic law
- inertia of the sheath neglected

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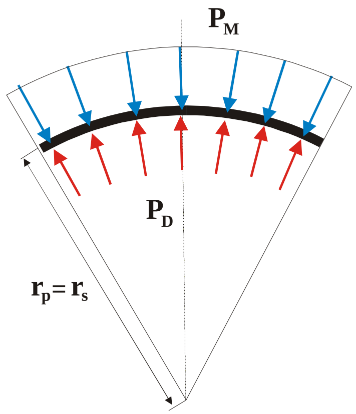
Snow-plow



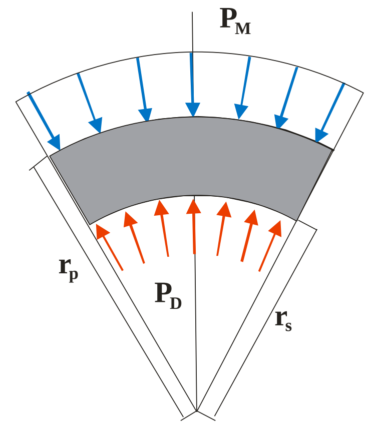
$$\frac{d(mv_p)}{dt} = 2\pi r_p P_m \quad \Rightarrow \quad v_p \frac{dm}{dt} + m\frac{dv_p}{dt} = 2\pi r_p P_m$$

$$m = m_0 + \pi\rho_0\left(R_0^2 - r_p^2\right) \quad \Rightarrow \quad \frac{dm}{dt} = 2\pi\rho_0 r_p \frac{dr_p}{dt}$$

$$m\frac{d^2 r_p}{dt^2} = 2\pi r_p P_m - 2\pi\rho_0 r_p v_p^2$$

$$\frac{dm}{dt} = 2\pi\rho_0 r_p \frac{dr_p}{dt}$$

Slug



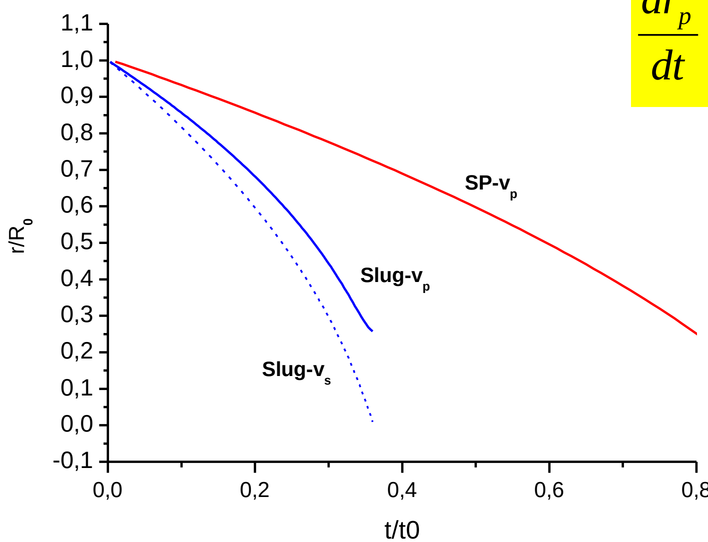
$$\frac{dp}{p} + \gamma\frac{dV}{V} = 0$$

$$p_m = \frac{2}{\gamma+1}\rho_0 \dot{r}_s^2 \quad \Rightarrow \quad \frac{dp_m}{p_m} = \frac{d\dot{r}_s^2}{\dot{r}_s^2} = \frac{2d\dot{r}_s}{\dot{r}_s} = 2\left(\frac{dI}{I} - \frac{dr_p}{r_p}\right)$$

for I=const.

$$V = r_p^2 - r_s^2$$

$$\frac{dr_p}{dt} = \left(\frac{2r_s}{(\gamma+1)r_p}v_s\right)\left(\frac{\gamma-1}{\gamma} + \frac{r_s^2}{\gamma r_p^2}\right)$$



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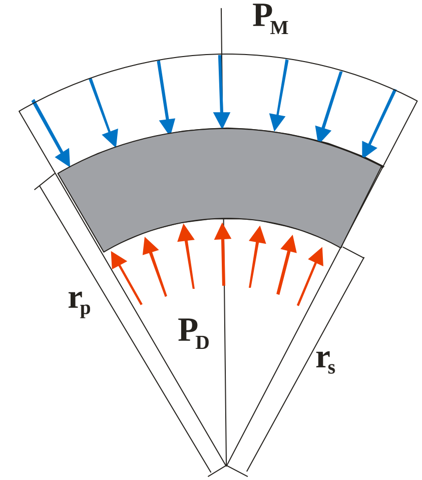
Snow-Plow-Slug – a proposal



$$\frac{d\dot r_p}{dt} = \frac{1}{M}\left[2\pi r_p \beta \frac{I^2}{r_p^2} - 2\pi\rho_0 r_s \dot r_s \dot r_p\right]$$

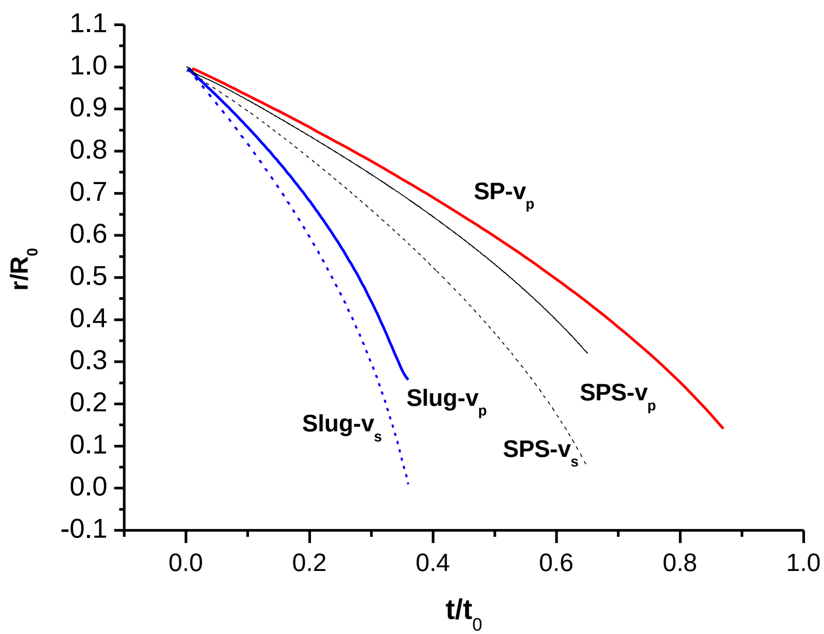
$$\frac{dp}{p} + \gamma\frac{dV}{V} = 0 \qquad P = \frac{2}{\gamma+1}\rho_0 \dot r_s^2 \qquad \Rightarrow \qquad \frac{dP}{P} = \frac{d\dot r_s^2}{\dot r_s^2} = \frac{2d\dot r_s}{\dot r_s}$$

$$\frac{2d\dot r_s}{\dot r_s} + \gamma\frac{2\left(r_p dr_p - \frac{2r_s}{\gamma+1}dr_s\right)}{\left(r_p^2 - r_s^2\right)} = 0$$

$$\ddot r_p = \frac{1}{M'}\left[\beta \frac{I^2}{r_p} - \rho_0 r_s \dot r_s \dot r_p\right]$$

$$\ddot r_s = -\gamma \frac{\dot r_s\left(r_p \dot r_p - \frac{2r_s}{\gamma+1}\dot r_s\right)}{\left(r_p^2 - r_s^2\right)}$$

$$\dot M' = -\rho_0 r_s \dot r_s$$




Thank you for attention