Relativistic shocks governed by Weibel turbulence and consequences

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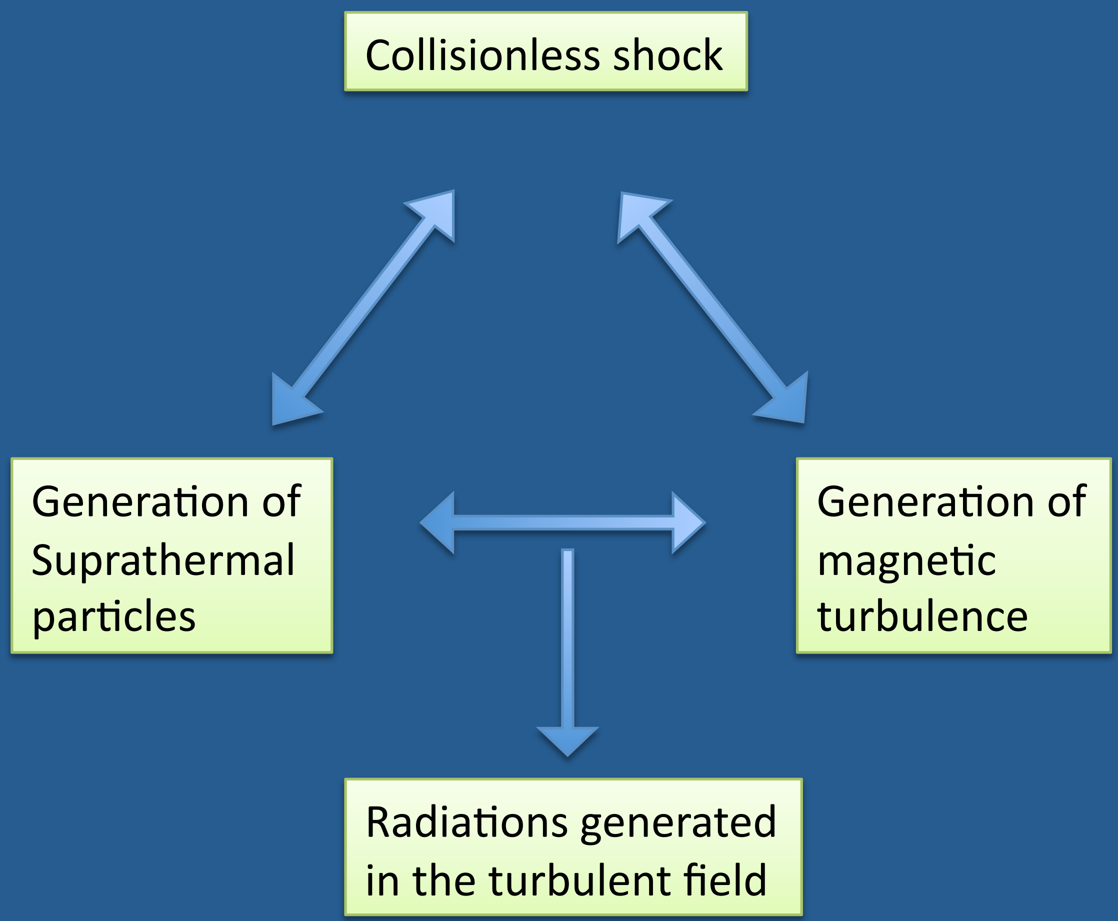
- generation of Weibel turbulence upstream,
  Properties of filaments, important issue of their motions
- electron pre-heating and consequences
- what about OTSI? And others?..
- implications on acceleration and radiative efficiencies

Plotnikov, Pelletier, Lemoine, arXiv 1206.6634. MNRAS submitted 12

Relativisitc shocks of low magnetization (termination shock of GRBs)

- A. Spitkovsky 08
- L. Sironi & A. Spitkovsky 10, 11
- Medvedev & Loeb 99
- J. Kirk & B. Reville 10
- G.P. , M. Lemoine, A. Marcowith 09
- M. Lemoine & G. P. 10, 11
- A. Achterberg & Wiersma 10
- A. Bret et al. 05->11
- Katz , Keshet, E. Waxman 09,...
- M. Dieckmann et al., 08 and ...
- Hededal & Nishikawa 05
- Lyubarsky & Eichler 09

The "3+1 paradigm"



Collisionless relativistic shock and the ambient plasma

- ambient plasma (upstream): $(n, B_0) \Rightarrow (\delta_i = c/\omega_{pi}, \sigma)$

Inertial scale, typical of microphysics

Magnetization parameter

$$\sigma \equiv \frac{B_{t|f}^2}{4\pi\Gamma_s^2\rho_u c^2} = \frac{B_0^2 \sin^2\theta_B}{4\pi\rho_0 c^2}$$

- collisionless R-shock: $\Gamma_s \gg 1$

Shocked plasma:
proton temperature $T_p \simeq 0.2\,\Gamma_s m_p c^2$
Electron temperature T_e ?

$$P_{th} = \frac{2}{3}\rho_u\Gamma_s^2 c^2$$

$$P_{cr} = \xi_{cr}\rho_u\Gamma_s^2 c^2$$

$$\frac{\delta B^2}{4\pi} = \xi_B\rho_u\Gamma_s^2 c^2$$

$$T \lesssim \Gamma_s m_p c^2$$

Main outcome : ξ_{cr} , ξ_B

Strong beam of reflected particles

- Ambient plasma pervaded by relat beam : $n_b\ \gamma_b\ m_p c^2$
with $n_b = \xi_b\, n$ $(\xi_b \simeq \xi_{cr})$ and $\gamma_b \sim \Gamma_s^2$

- Penetration length against ambient field :

A Larmor radius in front frame : $r_{L|f} = \frac{\Gamma_s m_p c^2}{e\Gamma_s B_{0t}}$

Penetration length measured in ambient frame : $\ell_p = \frac{m_p c^2}{e\Gamma_s B_{0t}} \simeq \frac{\delta_i}{\Gamma_s\sqrt{\sigma}}$

- growth length of Weibel (filamentation) instability :

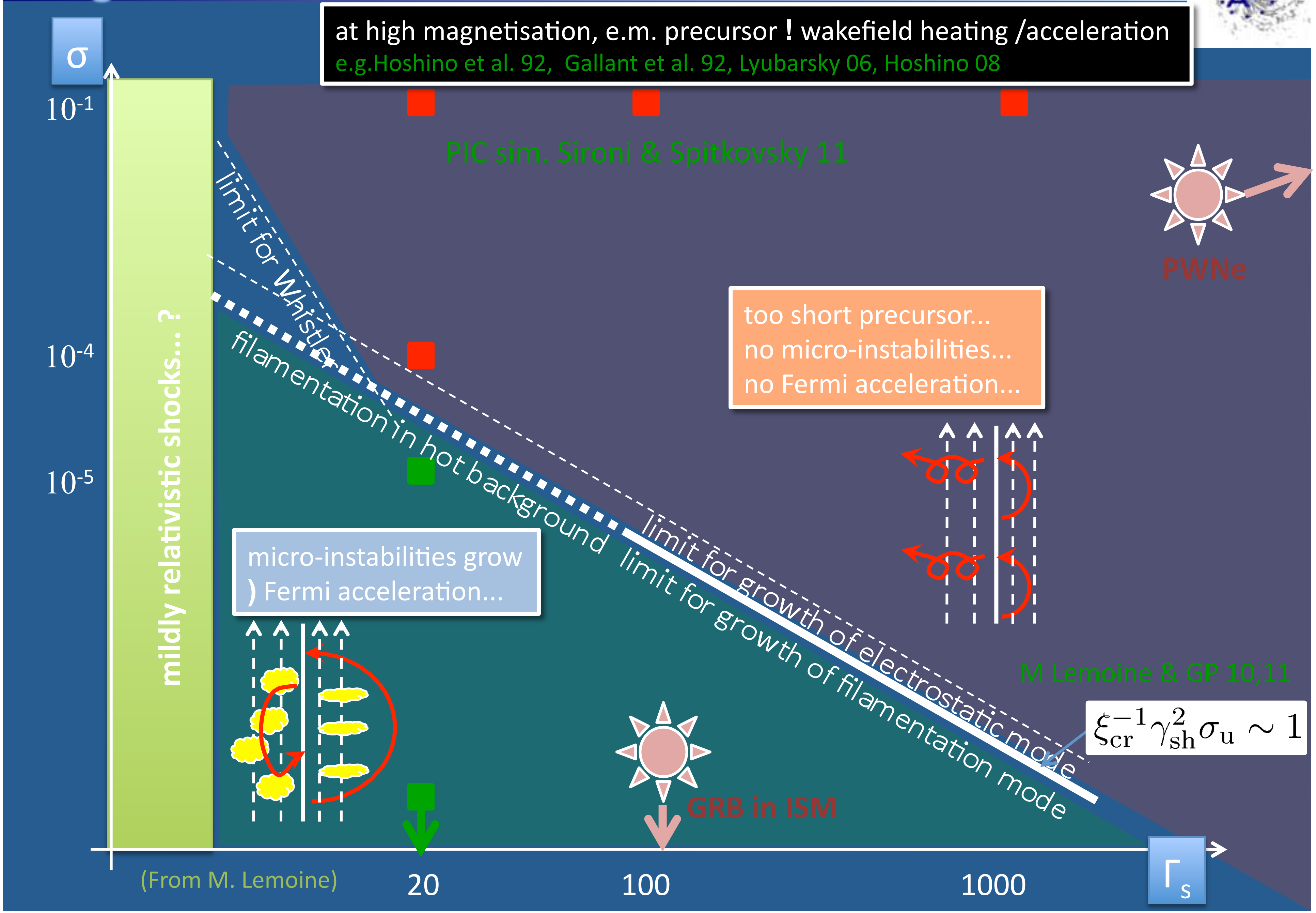
$$\ell_g \simeq \xi_{cr}^{-1/2}\delta_i\ (with\ \xi_b \simeq \xi_{cr})$$

Requirement for the generation of Weibel turbulence :

$$\ell_g < \ell_p \Longrightarrow \sigma < \frac{\xi_{cr}}{\Gamma_s^2}$$

M. Lemoine & GP 10

Magnetization vs shock Lorentz factor...



Reflection condition and level of Weibel turbulence

$$\frac{\text{growth time}}{\text{deflection time}} = \pi \qquad \Longrightarrow \xi_B \sim \xi_{cr}$$

builds a shock together with a piston effect

Unavoidable normal scale λ
The growth length :

$$\lambda \simeq \xi_{cr}^{-1/2} \delta_i \mathrm{Ln} \left(1 + \pi \sqrt{\frac{\xi_{cr}}{\sigma_\infty}}\right)$$

Scattering and electron heating analysed in the wave frame (Illya)

Particle motions in both static fields E′ and B′, same norm and orthogonal

Total energy conserved. In 2D generalized momentum conserved =>
Phase space confinement. 3D for scattering and heating.

Characteristic energy : $\epsilon_* \equiv e\bar{E}'\ell_c \sim \Gamma_m \xi_B^{1/2} \frac{\ell_c}{\delta_i} m_p c^2$

Scattering of beam particles

Fast heating of ambient electrons (relativistic regime) $T_e \sim \xi_B m_p c^2$

$\ell_c \sim \xi_B^{1/2} \delta_i$

Short heating scale $\ell_{heat} \sim \xi_{cr}^{1/2} \delta_i$

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Weibel modes and hot electrons

Filamentation instability, characteristics :

- For cold electrons

$$\omega = k_l V_m$$

Fast motion ! :

$$\Gamma_m \simeq (\xi_b \mu)^{-1/2} \sim 140$$

Growth rate :

$$\gamma_{inst} \simeq \xi_b^{1/2} \omega_{pi} \frac{k_t \delta_e}{1 + k_t^2 \delta_e^2}$$

Not at all frozen in upstream flow!

- For hot electrons ($T_e > m_e c^2$)

$$\mu \equiv \frac{\bar{\gamma}_e m_e}{m_p}$$

Despite ionic regime,
same growth rate !

Slowed down motion :

$$\Gamma_m \simeq \xi_b^{-1/2} \sim a\, few$$

Transverse scale δ_e (enlarged by increased mass)

Filament characteristics in the hot phase

Transverse confinement =>

$$\frac{|\delta n|}{n} T_e = \frac{\xi_B}{2} m_p c^2$$

$$T_e \sim \xi_B m_p c^2$$

$$\ell_c \sim \delta_e \sim \xi_B^{1/2} \delta_i$$

$$\frac{|\delta n|}{n} \sim 1$$

Reflection condition :

$$\xi_B \sim \xi_{cr}$$

$$\lambda \sim 10\, \xi_{cr}^{-1} \delta_i$$

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Shock transition, proton heating

Residual electron heating by scattering: similar amount as pre-heating

Thus finally $$T_e \sim \xi_B m_p c^2$$

Proton heating: mixing of the proton streams of energy $\Gamma_s\, m_p c^2$ at front.
Transition length controled by scattering:

$$T_p = \frac{1}{3\sqrt{2}} \Gamma_s m_p c^2$$

$$\delta_s \sim \frac{\delta_i}{\xi_B \Gamma_s}$$

(measured upstream)

Shock mediated by Weibel alone?

Because pe- plasma, electrostatic potential also.
For electrons, gradient of magnetic pressure,
balanced by a DC electric field.
The DC electric field slow down incoming protons.

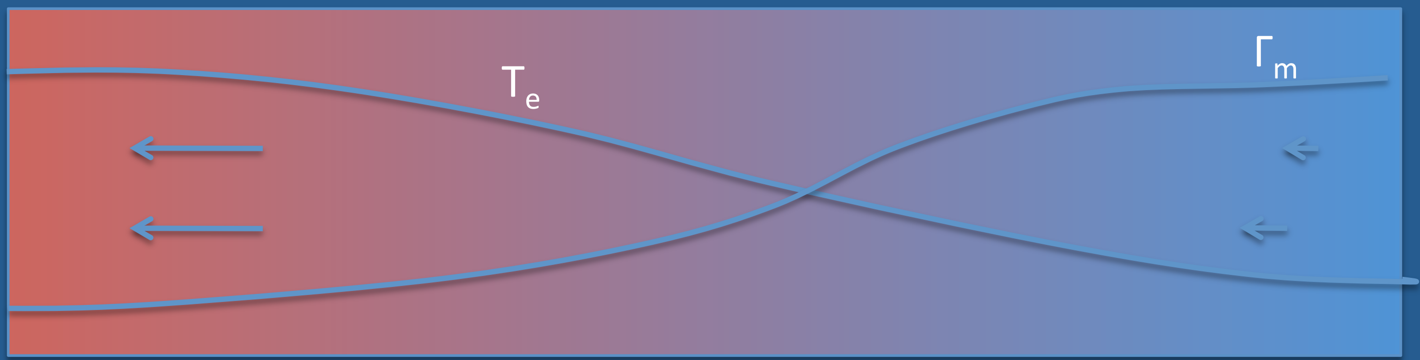
But $U_{el} \lesssim \xi_B \, m_p c^2$

Supplementary electron heating,
Same order of magnitude.
No significant modification of the
reflection condition for incoming protons.

The issue of filament motions and electron heating

Only Weibel modes survive in the hot phase (almost like e^+e^-)

Efficient acceleration in the cold phase



Pb : transmission downstream

$\Gamma_m \ll \Gamma_s$ => quasi vacuum e.m. waves

$\Gamma_m \sim \Gamma_s$ Favored for scattering downstream

$\Gamma_m > \Gamma_s$ Shock reformation?

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Residence time upstream

Measured in turbulence frame : $$t_{res,m} \sim \frac{\ell_c}{c}\left(\frac{\epsilon_{|m}}{\epsilon_*}\right)^2 \frac{1}{\Gamma^2_{f|m}}$$

Measured in front frame : $$t_{res,f} \sim \frac{\ell_c}{c}\left(\frac{\epsilon_{|m}}{\epsilon_*}\right)^2 \frac{1}{\Gamma^3_{f|m}}$$

$$t_{res|f} \sim \chi \frac{\ell_c}{c}\left(\frac{\epsilon_{|f}}{e\bar{B}_{|f}\ell_c}\right)^2 \frac{\Gamma_s}{\Gamma_m}$$

(Inverse compared to MHD)

χ large Γ_m/ξ_{cr} or more? (Illya) , 3D scattering pb

Performance of electron acceleration and radiation

At the termination shock of a GRB

(Kirk & Reville 2010 modified by Γ_m and chi)

$$\gamma_{\max} \sim \left(\frac{4\pi e^2 \ell_c}{\sigma_T m_e c^2}\frac{\gamma_m}{\chi\Gamma_s}\right)^{1/3} \sim (\mu n r_e^3)^{-1/6}\left(\frac{\gamma_m}{\chi\Gamma_s}\right)^{1/3} \sim$$

$$\sim 7\times 10^6 \left(\frac{\gamma_m}{\chi\Gamma_s}\right)^{1/3} .$$

$$\epsilon_{\gamma,\max} \sim \Gamma_s \gamma_{max}^2 \frac{\hbar e \bar{B}_{|f}}{m_e c^2} \sim \sqrt{\xi_B}\frac{\Gamma_s^{4/3}(\gamma_m/\chi)^{2/3}}{(\mu n r_e^3)^{-1/6}}\frac{m_p c^2}{\alpha_f} \simeq$$

$$\simeq 3\times \xi_{B,-2}^{1/2}\Gamma_{s,2.5}^2 n_0^{1/2}\left(\frac{\gamma_m}{\chi\Gamma_s}\right)^{2/3} \text{GeV} ,$$

Pb of the 3D scattering ↑

A single synchrotron-like spectrum up to a few GeV !..

Performance of proton acceleration

Termination shock of GRBs a poor proton accelerator…

(because of a scattering time ∝ ϵ^2)

$$
\begin{aligned}
E_{\max} &= 2Z\Gamma_{\rm s}\left(\frac{\gamma_{\rm m}}{\chi}\right)^{1/2}\xi_{\rm B}^{1/2}\sqrt{\frac{r_{\rm s}}{\delta_{\rm i}}}\,m_p c^2 \\
&\sim 3.7\times 10^{15}\times Z\left(\frac{\gamma_{\rm m}}{\chi}\right)^{1/2}\Gamma_{\rm s,2.5}r_{\rm s,17}n_0^{1/4}\ eV\ .
\end{aligned}
$$

About the contribution of OTSI

Selection of a single k_l through resonance condition :

$$\omega(k) - k_l v_b = 0$$

Growing faster than Weibel :

$$\gamma_{inst} \sim (\xi_b \mu)^{1/3} \omega_{pe}$$

Particle dynamics studied in wave-frame (Illya)

$$\Gamma_w \simeq (\xi_b \mu)^{-1/6} \ll \Gamma_s$$

Fast electron heating (relativistic oscillation regime)

Instability quenched by beam dispersion and/or
relativistic electron temperature whereas Weibel survive!
Langmuir waves become superluminal
(resonance no longer possible).
Thus OTSI modes do not survive in the hot phase,
but probably dominate the cold phase. (Possibly with whistlers)

About Buneman instabilities

The fastest growing modes, but rapidly quenched by electron heating

Also, whistlers expected for mildly relat shocks.
(limitation when electron mass becomes relativistic)

Generation of UHECRs

Better with mildly relativistic shocks in relativistic flows:
AGN and radio galaxy jets,
internal shocks in GRBs.

$$\gamma_s(\gamma_s - 1) \sim 1$$

Phase space more easily opened despite a sub-equipartition mean field;
MHD turbulence more easily excited with Bell-type instability.

$$\epsilon_{\rm max} \simeq \Gamma_j Z e \bar{B} r_j \simeq Z \times 10^{19} \left(\frac{\xi_B}{10^{-2}} \frac{P_{\rm jet}}{10^{45}\,{\rm erg/s}} \right)^{1/2} \;{\rm eV}$$

Summary: properties of a CR-shock governed by micro-turbulence

The scales, all in terms of δ_i, in the hot phase :

Shock front width: $\delta_s \sim \frac{\delta_i}{\xi_B \Gamma_s}$

Weibel growth length: $\ell_g \sim \xi_{cr}^{-1/2} \delta_i$

Filament radius: $\ell_c \sim \xi_B^{1/2} \delta_i$

Coherence scale: $\ell_c \sim \xi_B^{1/2} \delta_i$

Filament length: $\lambda \sim 10\, \xi_{cr}^{-1/2} \delta_i$

Heating length: $\ell_h \sim \xi_{cr}^{1/2} \delta_i$

$$T_e \sim \xi_B m_p c^2 \ upstream$$

$$T_e \sim \xi_B \Gamma_s m_p c^2 \ downstream$$

The two parameters $\xi_B \sim \xi_{cr}$