# Design guidance for the flowing lithium systems in tokamaks[1]

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# Contents

***Reference (LiLi) parameters***

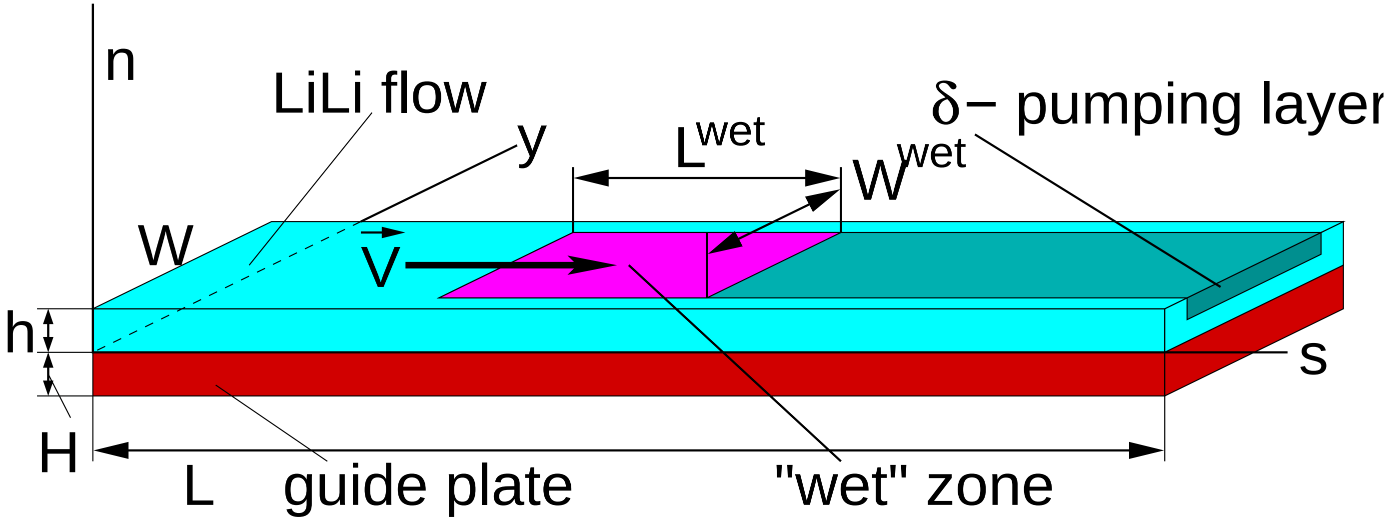
| | | | | | | |
|---|---|---|---|---|---|---|
| 1. | * | $A$ | 6.941 | | Atomic mass | |
| 2. | * | $\rho$ | 0.495 | $\frac{g}{cm}$ | Density | half water density |
| 3. | * | $T_m$ | 180.54 | $^oC$ | Melting temperature | |
| 4. | * | $T_b$ | 1347 | $^oC$ | Boiling temperature | |
| 5. | * | $Q_{melt}$ | 0.432 | $\frac{kJ}{g}$ | Heat of fusion | larger than water |
| 6. | *** | $Q_{vapor}$ | 20.9 | $\frac{kJ}{g}$ | Heat of vaporization | |
| 7. | * | $c_p$ | 4253 | $\frac{J}{kg\cdot K}$ | Thermal capacity | like water |
| 8. | ** | $\kappa_T$ | 47.6 | $\frac{MW}{m^2}$ | Thermal conductivity at 600$^o$ K | $\frac{MW}{m^2}$ at $T' = \frac{210^o}{mm}$ |
| 9. | ** | $\sigma$ | 3.4·$10^6$ | $\frac{1}{\Omega\cdot m}$ | Electric conductivity at 600$^o$ K | 1/17.5 of copper |
| 10. | ** | $\nu$ | 0.42·$10^{-3}$ | $Pa \cdot s$ | Viscosity $\nu$ at 600$^o$ K | like water |
| 11. | * | $\sigma_T$ | 0.339 | $\frac{N}{m}$ | Surface tension at 600$^o$ K | |

*[*] “Handbook of Physical Quantities”, Ed. by Igor S.Grigoriev and Evgenii Z. Melnikov, Russian Research Center “Kurchatov Institute”, Moscow, Russia. CRC press, Boca Raton, New York, London, Tokio (ISBN 0-8493-2861-6)*

*[**] "Handbook of Thermodynamic and Transport Properties of Alkali Metals", Editor Roland W. Ohse, Blackwell Scientific Publications, Oxford, London, Edinburgh, Boston, Palo Alto, Melbourne (ISBN 0-632-01447-4).*

*[***] Internet*

# Geometry of LiLi flow in tokamaks




| | | |
|---|---|---|
| $\boldsymbol{H}$ | [mm] | *thickness of the guide plate,* |
| $\boldsymbol{L}$ | [m] | *length of the LiLi flow,* |
| $\boldsymbol{W}$ | [m] | *width of the flow,* |
| $\boldsymbol{h}$ | [mm] | *thickness of the flow,* |
| $\boldsymbol{L^{wet}}$ | [m] | *length of the contact zone,* |
| $\boldsymbol{W^{wet}}$ | [m] | *width of the contact zone,* |
| $\boldsymbol{\delta}$ | [mm] | *thickness of the active pumping layer,* $\delta_{mm} \simeq \min\left\{0.1\sqrt{t_{exposure}}, h_{mm}\right\}$ |

*In tokamaks*

$$\delta \le h \ll W, L \tag{1.1}$$

*Free side and side wall restrained flows are considered.*

*Use of LiLi can address several fundamental issues in tokamak fusion:*

1. ***Power extraction with high temperature LiLi,*** $T_{LiLi} > 450^oC$. *In addition, if successful, this would:*
   (a) *protect the in-vessel structures,*
   (b) *establish the stationary plasma-wall interactions,*
   (c) *solve the problem of stationary boundary conditions for the plasma itself.*

2. ***LiWall Fusion (LiWF) regime: plasma particle pumping with*** $T_{LiLi} < 400^o$ **C.** *As a result, in combination with NBI, this would:*
   (a) *establish the best possible, diffusion based confinement regime (if* $R^{ecycl} < 0.5$ *achieved), eliminate the effect of anomalous electron thermal conduction,*
   (b) *extend the present "hot-ion" regime to burning plasma,*
   (c) *significantly reduce the external heating power,*
   (d) *make core temperature profile stationary,*
   (e) *stabilize the core sawtooth instability,*
   (f) *eliminate the Greenwald limit for disruptions,*
   (g) *provide stationary boundary conditions for the plasma.*

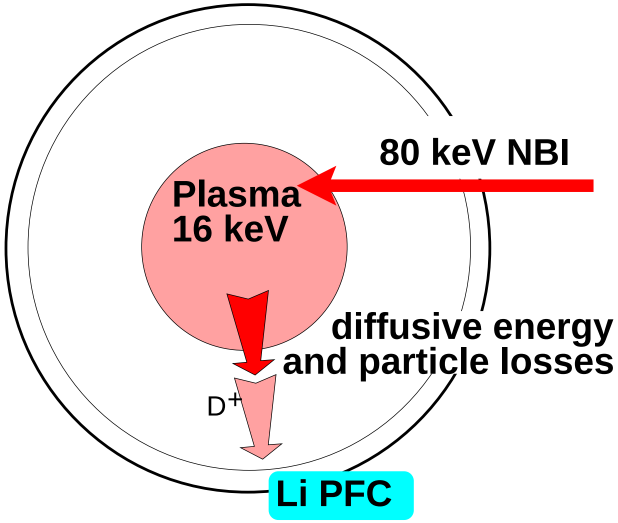
***The first option, as well as Li conditioning, represent only partial improvements of conventional approach to fusion, leaving many long standing fundamental problems unsolved.***

***The practical approach to fusion is based on understanding that***

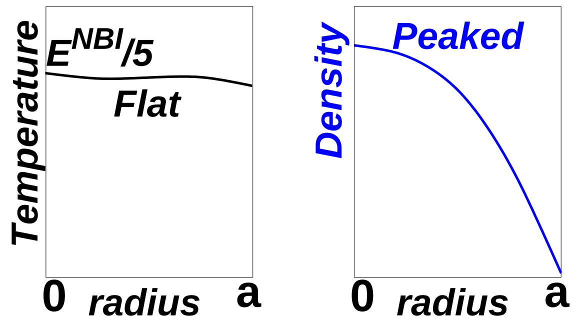
***For toroidal plasma is much more efficient to prevent its cooling by flux of neutrals to the plasma edge, rather than to rely on extensive heating power, big size, stong fields, etc.***

# The LiWall Fusion (LiWF)

***NBI for core fueling & heating + Pumping LiWall conditions***
***(no edge cooling: gas puff $+$ recycling $\leq$ NBI particle source)***




**In LiWF the high edge T is OK**




*No plasma physics effects (ITG/ETG, sawteeth, ELMs)*

*Stability is excellent. LiWF relies only on external control.*

*Entire plasma volume is used for fusion*

***The BEST possible, diffusion based, confinement regime with the simplest possible plasma physics***

***Anomalous electron thermal conduction plays no role***

***The LiWF regime was suggested as the burning plasma regime for the 100 MW Fusion-Fission Research Facility (FFRF) - one of options for the next step in China fusion.***

*The talk is focused on stationary LiLi systems with $T_{LiLi} < 400^oC$ for particle pumping and power extraction relevant to the LiWF development*

# 2 Necessary rate of LiLi replenishment

*The typical particle flux to the wall in tokamaks can be assessed as*

$$\frac{dN}{dt} = \frac{10^{22}}{s}. \tag{2.1}$$

*In the LiWF regime this number is expected to be 30-50 times smaller.*

*With LiLi absorbing capacity as 10 % (atomic) this would require replenishment rate of Li of only*

$$\frac{dN_{LiLi}}{dt} = \frac{10^{23}}{s}, \qquad \left.\frac{dLiLi}{dt}\right|_{Liter/s} = 2 \cdot 10^{-3}. \tag{2.2}$$

*The minimal velocity required*

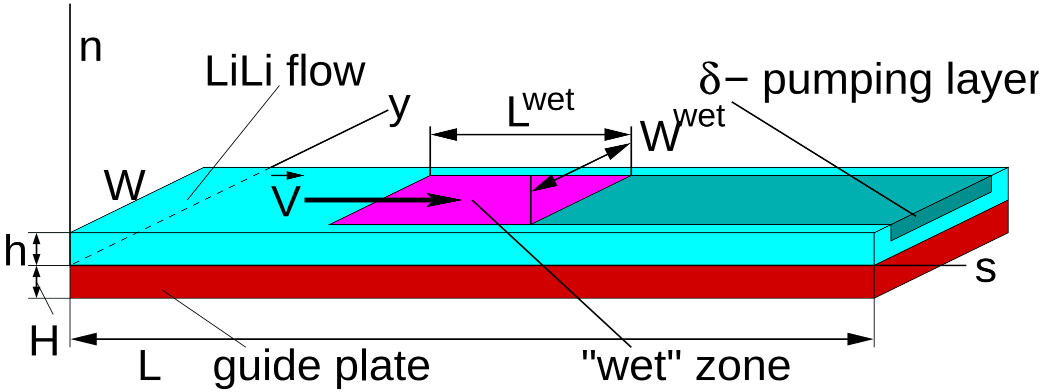
$$V_{cm/s} = \frac{2_{cm^3/s}}{\delta_{cm} \cdot L_{cm}} = \frac{0.2}{\frac{\delta_{cm}}{0.1_{cm}} \cdot \frac{W_{\delta,cm}}{100_{cm}}}, \quad W_\delta \le W = W_{flow}. \tag{2.3}$$

*For EAST LiLi particle pumping system*

$$R = 1.8\ m, \quad W_{LiLi} = 11.3\ m, \quad \delta = 0.1\ mm, \tag{2.4}$$

*the required velocity is miniscule and*

$$V_{cm/s} \simeq 0.2, \qquad \left.\frac{dLiLi}{dt}\right|_{Liter/s} = 2 \cdot 10^{-3} \tag{2.5}$$




$W_\delta$ *- width of the contact zone,*

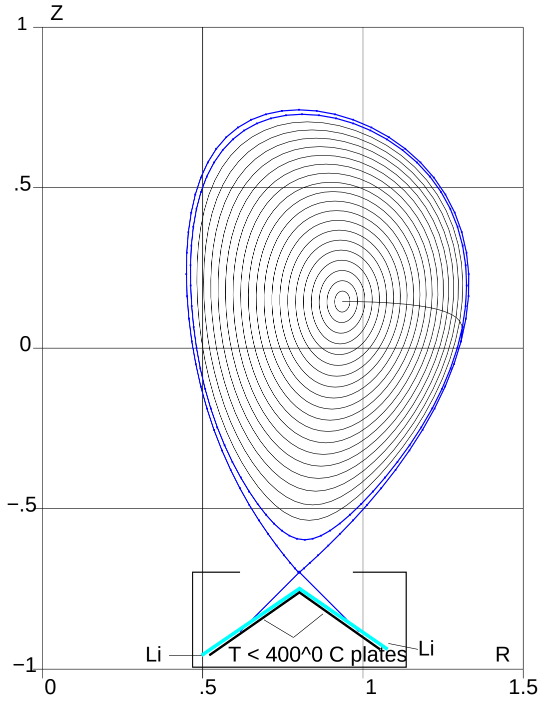
$\delta$ *- thickness of the active pumping layer*

$h$ *- total thickness of LiLi.*

$$\delta_{mm} = \min\left\{0.1\sqrt{t_{exposure}}, h_{mm}\right\}$$

***For pumping the required rate of replenishment of LiLi is not a challenge***

# 3 Thin LiLi layer on the top of a heat sink




This LiLi layer at the surface of actively cooled target plates

***The primary option:*** *thin ($\simeq 0.1$ mm) slowly ($V < 1$ cm/sec) moving LiLi layer with heat extraction by the guide plate.*

*It represents the simplest system satisfying requirements of the LiWF regime.*

*The temperature drop across the LiLi layer:*

$$\Delta T_{LiLi} \simeq 100^o \frac{q_{surf}}{47\ MW/m^2} \cdot \frac{h_{LiLi}}{0.1\ mm} \qquad (3.1)$$

*($q_{surf}$ is the heat flux, $h_{LiLi}$ is the the thickness of the layer) Viscose force is dominant*

$$\nu \Delta V \simeq 0.8 V \left(\frac{0.1\ mm}{h}\right)^2 \left[\frac{Atm}{m}\right] \qquad (3.2)$$

***The LiLi with $h \simeq 0.1$ mm itself does not limit the power extraction from tokamak.***

***It is also compatible with particle pumping and other requirements on the LiLi system for the LiWF regime.***

*With a heat sink based on oxide-dispersion strengthened copper the thin LiLi layer is compatible with neutron irradiation.*

***The ideas of using LiLi for power extraction significantly complicate the system.***

***Basic relationships:*** *increase in the surface temperature* $\Delta T_{LiLi}$:

$$\Delta T_{LiLi} = q_{surf}\sqrt{\frac{4t_{exposure}}{\pi\kappa\rho c_p}}, \quad d_{skin} \equiv \sqrt{D^{wet}_{LiLi}\cdot t_{exposure}}, \quad D^{wet}_{Li} \equiv \frac{\kappa}{\rho c_p}, \qquad (4.1)$$

*where* $q_{wall}$ *is the power flux,* $d_{skin}$ *is the heat penetration depth.*

*For LiLi*

$$(k_T\rho c_p)_{Li} = 1.00\left[\frac{J^2}{sec\cdot K^2 cm^4}\right], \qquad D^{wet}_{LiLi} = 0.21\,\frac{cm^2}{s}. \qquad (4.2)$$

$$\Delta T_{Li}Li = 200^o\frac{q_{surf}}{1.75\ MW/m^2}\sqrt{t_{exposure}}, \qquad d_{skin} = 4.8\sqrt{t_{exposure}}\ mm. \qquad (4.3)$$

# Power extraction by flowing lithium

*Driven Lithium Streams for heat extraction:*

$$t_{exposure} = \frac{V}{L^{wet}}, \quad V_{m/s} = 0.33 L_m^{wet} \left[ \frac{q_{surf}}{1_{MW/m^2}} \frac{200^o}{\Delta T} \right]^2, \qquad d_{skin,mm} = 4.8 \sqrt{\frac{L}{V}}. \qquad (4.4)$$

***These estimates are general and do not depend on the mechanism driving the flow.***

*They essentially rule out the use of LiLi flow for heat removal from tokamak*

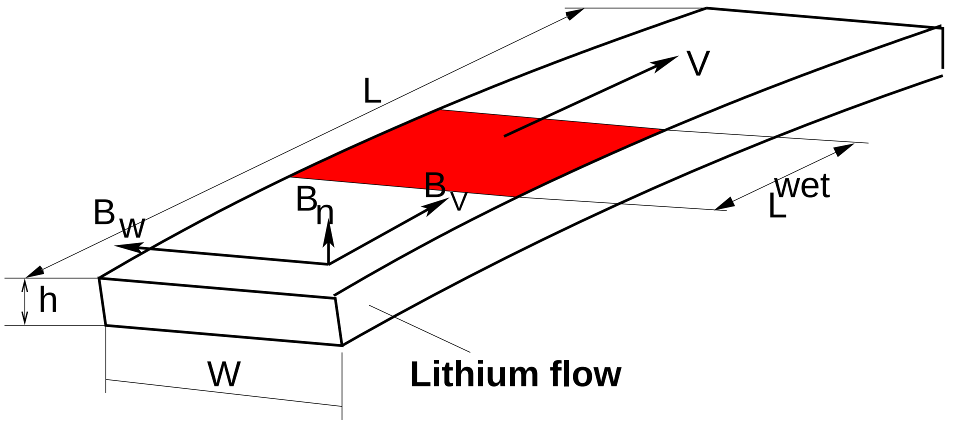
| | LiWall Fusion regime | | Conventional regime |
|---|---|---|---|
| Reference parameters | EAST | FFRF, $100\ MW^{DT}$ | ITER-like FFH, $100\ MW^{DT}$ |
| $R_m$ | 1.8 | 4 | 4 |
| $L_m^{wet}$ | 0.1 | 0.1 | |
| $P_{SoL,MW}$ | 3 | 10 | 40 |
| $q_{MW/m^2}$ | 2.7 | 4 | 16 |
| $V_{LiLi,m/s}$ | $> 0.24$ | $> 0.56$ | $> 8.6$ |
| $d_{mm}$ | $3.1$ | $2.0$ | $0.5$ |
| $\frac{dLi}{dt}\|_{Liter/s}$ | $8.1$ | $28.1$ | $> 108$ |

***For heat removal $V_{LiLi}$ is much larger than $0.2$ cm/s, required for particle pumping.***

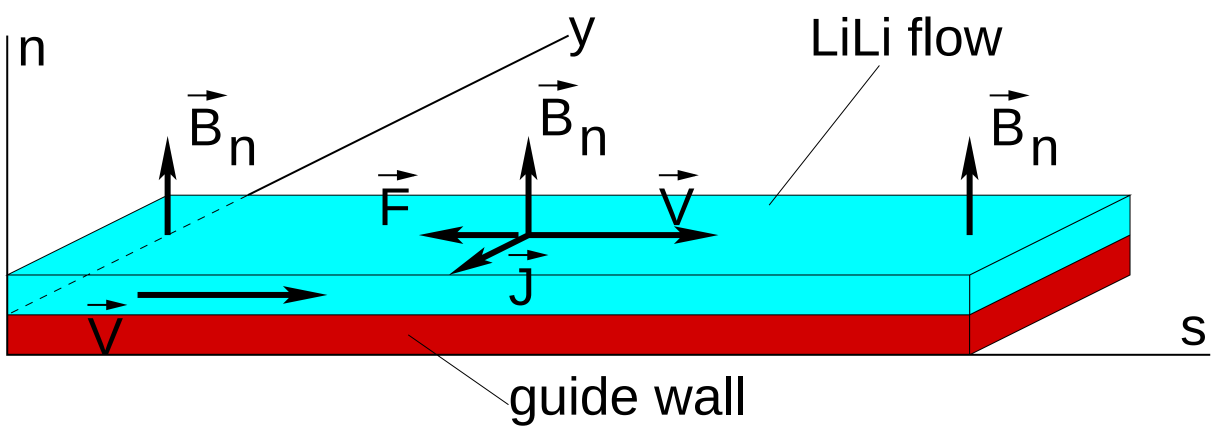
***Free flow:***

*The thickness $h$ of the flow determines 3 important magnetic Reynolds numbers which control MHD LiLi in tokamaks:*

| | | | |
|---|---|---|---|
| *for LiLi* $\Re_0 = \mu_0\sigma LV \simeq 4LV$ | $\propto h^0$ | *important for dynamics,* | $\Re_0$ *is big* *associated* $B_n^2/2\mu_0$ *is small* |
| $\Re_1 = \mu_0\sigma hV \simeq 4hV$ | $\propto h^1$ | *important for electro-dynamics* | *at* $\Re_1 \simeq 1$ *the LiLi flow perturb* $\mathbf{B}$ |
| $\Re_2 = \mu_0\sigma \frac{h^2}{L_B}V \simeq 4\frac{h^2}{L_B}V$ | $\propto h^2$ | *important for dynamics* | $\Re_2$ *is small,* *associated* $B_w^2/2\mu_0$ *is big* |



# 4.2 Pressure drop due to Bn

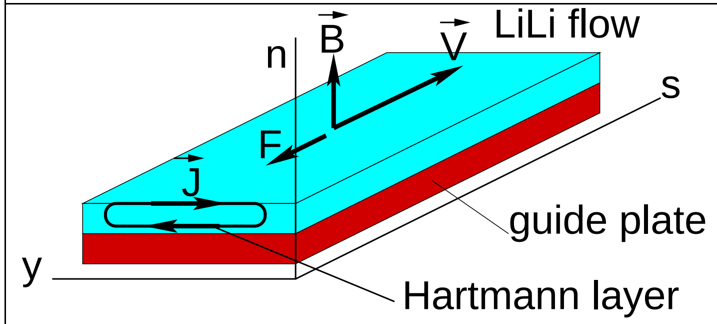



***Hartmann field:***

$$B_H \equiv \frac{1}{h}\sqrt{\frac{\nu}{\sigma}} = \frac{1.13 \cdot 10^{-2}}{h_{LiLi,mm}}$$

*LiLi in tokamaks is always in the Hartmann regime*

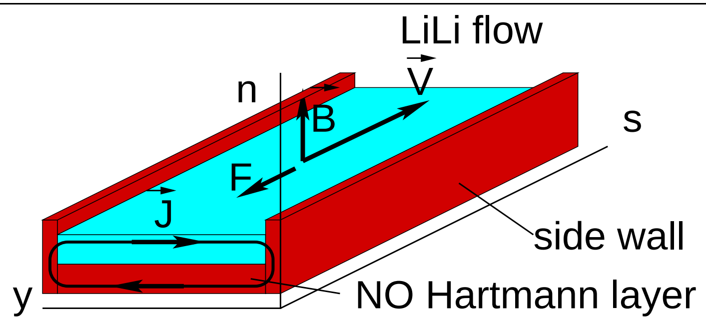
### *Free sides flow*




*Pressure drop:*

$$\Delta p \simeq \frac{2\mathcal{R}_0}{\frac{B_H}{B_n}\sinh\frac{B_n}{B_H}}\frac{B_n^2}{2\mu_0}$$

### *Flow within side wall*

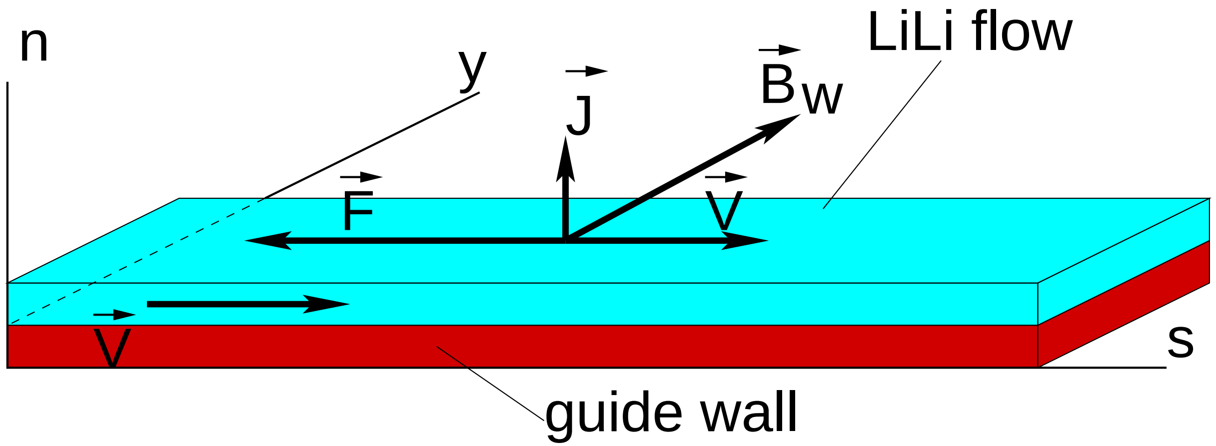



*Pressure drop:*

$$\Delta p \simeq 2\mathcal{R}_0\frac{B_n^2}{2\mu_0}$$

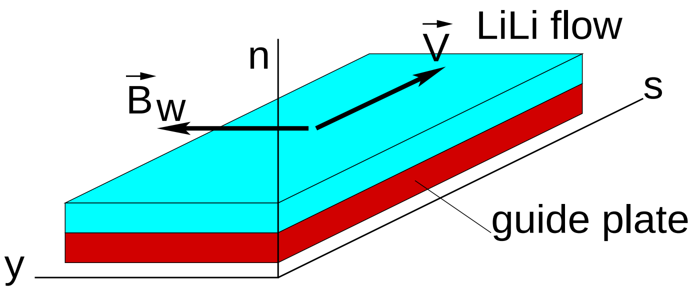
***Drag force due to the normal magnetic field to the walls acts along the entire flow path and makes the flow pattern complicated.***

# 4.3 Pressure drop due to Bw with the side walls



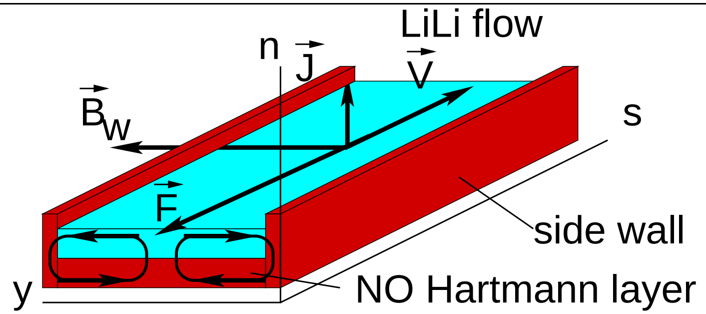

***$B_w$ is the toroidal magnetic field of tokamaks***

***Free sides flow***




*No drag force*

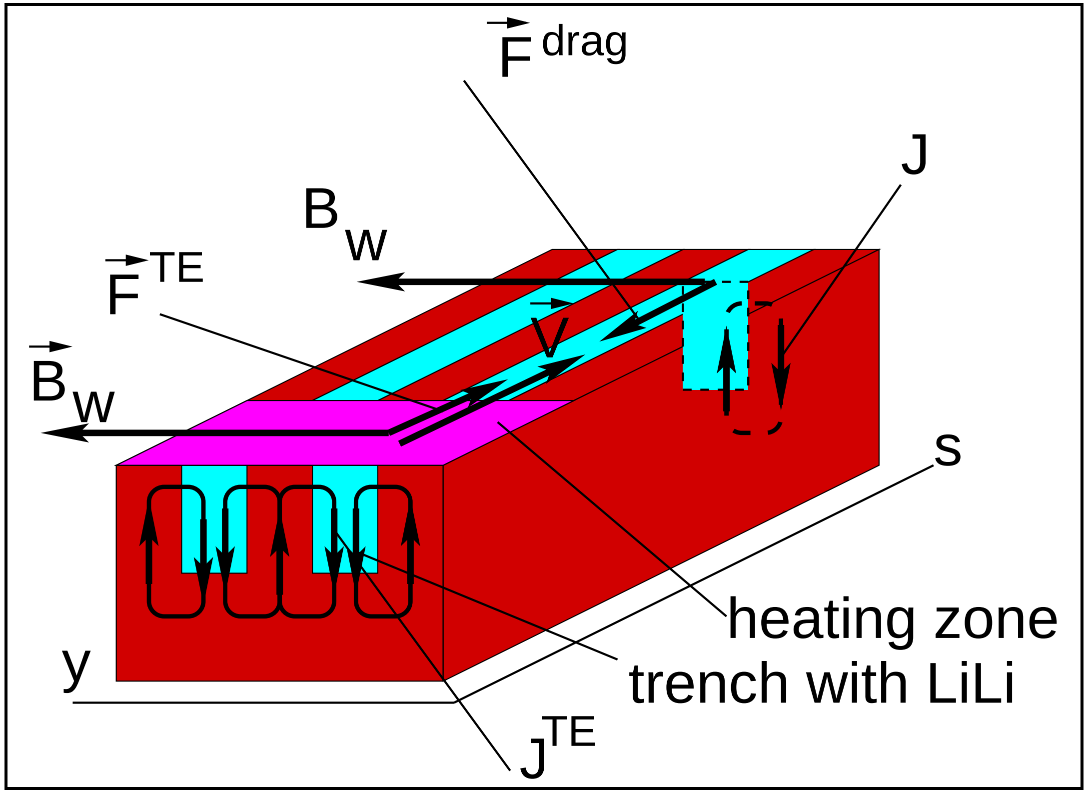
***Flow within side wall***




*Huge pressure drop:* $\Delta p \simeq 2\mathcal{R}_0 \cdot \frac{h}{w} \cdot \frac{B_w^2}{2\mu_0}$

***Any side walls perpendicular to the toroidal magnetic field create very big drag force, 5T is equivalent to 100 atm***

# 4.4 Thermo-electric (TE) drive




***Expected TE current density LiLi/SS***

$$j^{TE} \simeq \sigma \Delta S \frac{\Delta T}{h}, \quad \Delta S \simeq 25 \cdot 10^{-6} \left[\frac{V}{K}\right]. \tag{4.5}$$

***LiLi velocity***

$$V_{LiLi} < V^{drift} = \frac{\Delta S}{B_w}\frac{\Delta T}{h}. \tag{4.6}$$

***Pressure balance***

$$j_{TE} B_w L = 2\mu_0 \sigma L V \cdot \frac{h}{w} \cdot \frac{B_w^2}{2\mu_0}. \tag{4.7}$$

$$V \simeq \frac{\Delta S}{B_w}\frac{\Delta T}{h} \cdot \min\left\{\frac{w}{h}, 1\right\} \tag{4.8}$$

***The optimal*** $w \simeq h$, $\quad V_{max} \simeq \frac{2.5}{h_{mm}} \cdot \frac{2}{B_w} \cdot \frac{\Delta T}{200^o}, \quad q_{surf,MW/m^2} = 8.75 \frac{\Delta T}{200^0} \sqrt{\frac{V}{2.5} \cdot \frac{0.1}{L^{wet}}}. \qquad (4.9)$

***If LiLi has lost its $\nabla T$, the drag force will stop LiLi flow almost instantaneously***

$$\rho \frac{V^2}{2} = 2\mathcal{R}_0 \cdot \frac{h}{w} \cdot \frac{B_w^2}{2\mu_0}. \tag{4.10}$$

$$L_{mm\ !!!} \simeq \frac{0.05}{h_{mm}} \cdot \frac{8}{B_w^3} \cdot \frac{\Delta T}{200^o} \cdot \frac{w}{h}. \tag{4.11}$$

# There is no simple solution based of TE effect

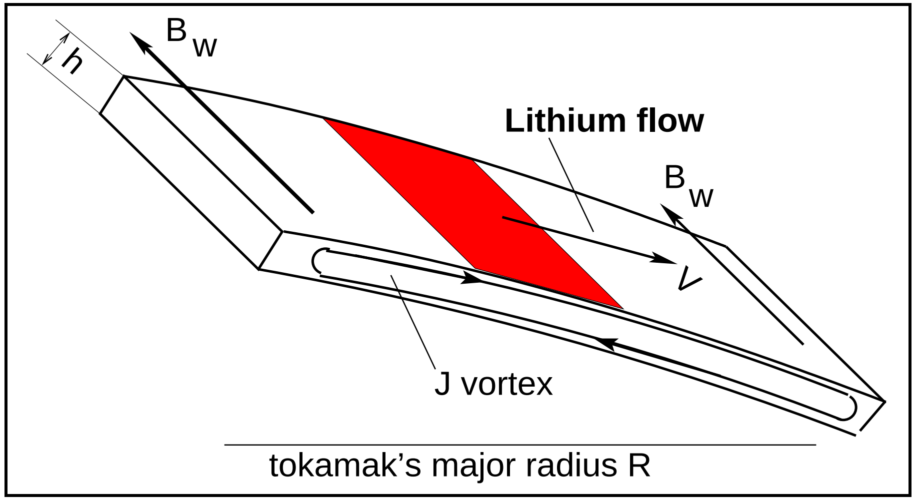

***TE effect in LiLi MHD was recently discovered by D.Ruzic group as a new, strong mechanism affecting the flow. TE should be taken into account in designing flowing LiLi systems and, potentially, utilized.***

*At the same time, the drag force associated with the pressure of the toroidal magnetic field introduces significant complications in utilizing the TE drive.*

***E.g., in the case of simplistic implementation, the flow in HT-7 would be still in front of and behind the heat zone.***

$$L_{mm\ !!!} = 0.05 \cdot \frac{8}{B_w^3} \cdot \frac{\Delta T}{200^o} \cdot \frac{w}{h} \simeq 0.05. \tag{4.12}$$

***TE effects may open opportunities for driving LiLi through thin porous layer at the top of the heat sink for LiLi replenishment purposes, rather than for heat removal.***




***Pressure drop due to the drag force***

$$\Delta p \simeq -\frac{1}{2}\mu_0 V h^2 \left|\nabla \frac{B_w^2}{2\mu_0}\right| = -\frac{1}{2}\Re_2 \left|\Delta \frac{B_w^2}{2\mu_0}\right|. \qquad (4.13)$$

***The effect is:***

1. ***important for $h > 1$ cm because of large value of $B_w = B_{tor}$;***
2. ***unavoidable and insensitive to $L$***

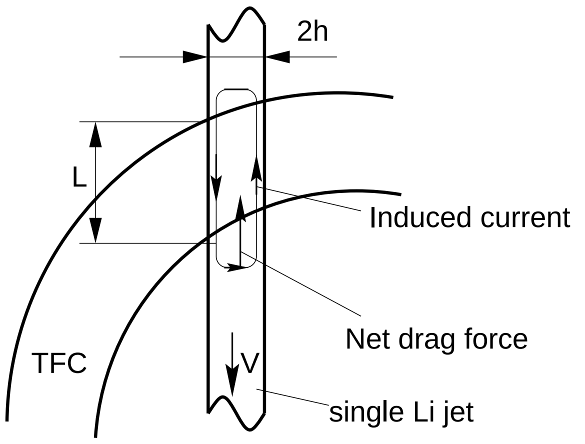
***All potential closed loops are challenged by the drag force associated with the gradient of the toroidal magnetic field of tokamaks.***

# MHD of metal jets

**Metal jets are free from wall effects**

*Electric current in fast jets is excited because of inhomogeneity of the magnetic field. Its interaction with the magnetic field leads to losses in kinetic energy*

$$\left\langle \Delta \frac{\rho V_z^2}{2} \right\rangle_{jet} = -\frac{1}{2}\Re_2 \Delta \frac{B_0^2}{2\mu_0}, \quad \left\langle \Delta \frac{\rho V_z^2}{2} \right\rangle_{film} = -\frac{2}{3}\Re_2 \Delta \frac{B_0^2}{2\mu_0}, \quad \Re_2 \equiv \frac{\mu_0 \sigma h^2 V}{L} \ll 1 \tag{4.14}$$




$$\rho \frac{\partial \mathrm{V}}{\partial t} + \rho(\mathrm{V}\cdot\nabla)\mathrm{V} = -\nabla p + (\mathrm{j}\times\mathrm{B}) + \nu\Delta\mathrm{V},$$

$$\frac{\partial \mathrm{A}}{\partial t} - \nabla\varphi_E + (\mathrm{V}\times\mathrm{B}) = \frac{\mathrm{j}}{\sigma},$$

$$\mathrm{B} = B(s)\mathrm{e}_y, \quad \mathrm{V} = V\mathrm{e}_s,$$

$$\mathrm{j} = (\nabla i \times \mathrm{e}_y) = -i'_s \mathrm{e}_x + i'_x \mathrm{e}_s,$$

$$i_{jet} = -\sigma \frac{h^2 - y^2 - x^2}{2}(VB)'_s,$$

$$i_{film} = -\sigma \frac{h^2 - x^2}{2}(VB)'_s$$

$$\frac{\rho}{2}(V_s^2)'_s = ((\mathrm{j}\times\mathrm{B})\cdot\mathrm{e}_s) = j_x B = -i'_s B$$

$$\frac{\rho}{2}(V_s^2)'_s = \sigma \frac{h^2 - y^2 - x^2}{2}[(VB)'_s]'_s B.$$

**"Sausage"-like instability is an issue**

*Metal jets exhibits a "sausage"-like instability due to the high surface tension of the liquid metals*

$$\gamma = \sqrt{\frac{T}{h^3\rho}\frac{khI_0'(kh)}{I_0(kh)}(1-k^2h^2)}, \quad \gamma_{max}|_{kh=0.697} = 0.3433\sqrt{\frac{T}{h^3\rho}} = 0.97\sqrt{\frac{T}{d^3\rho}}, \qquad (4.15)$$

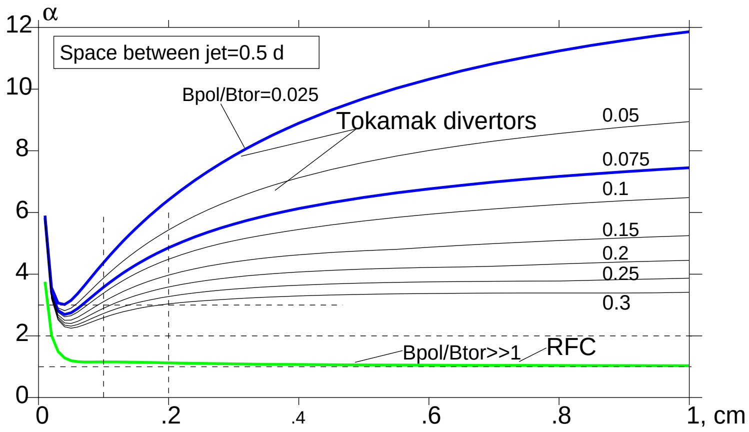
*where $T$ is the surface tension, $k$ is the wave-vector, $h$ is the radius and $d$ is the diameter of the jet.*

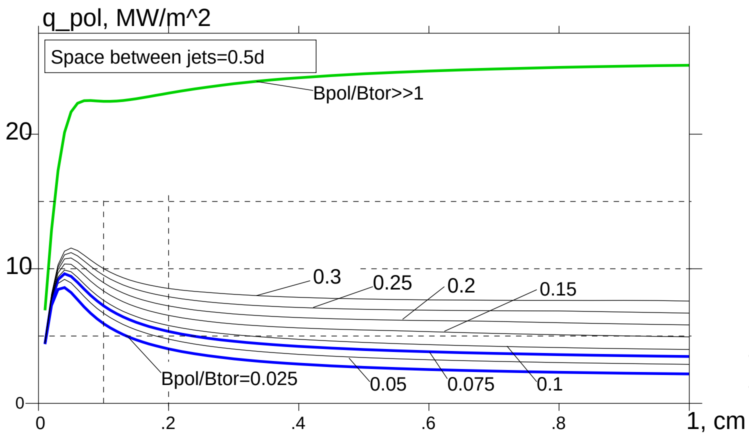
| Characteristics of instability | | Li 300$^o$ C | Ga 300$^o$ C | SnLi 300$^o$ C | |
|---|---|---|---|---|---|
| $\rho$ | | 0.53 | 6.1 | 6.8 | [g/cm$^3$] |
| $T$ | | 380 | 700 | 500 | $10^{-3}$[N/m] |
| $\gamma = .97\sqrt{\frac{T}{d^3\rho}}$ | $d = 0.5\ cm$ | 26.0 | 10.4 | 8.3 | [1/sec] |

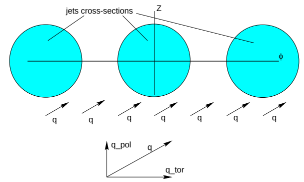
# Numerical modeling

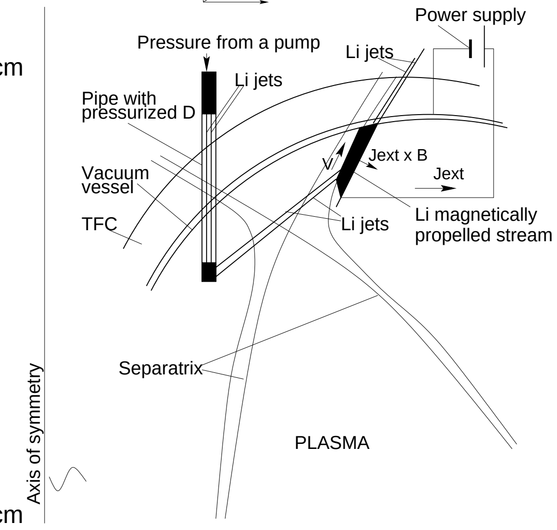
## Leading edges of jets are the issue for power extraction: $\alpha > 1$ reflects inhomogenuity

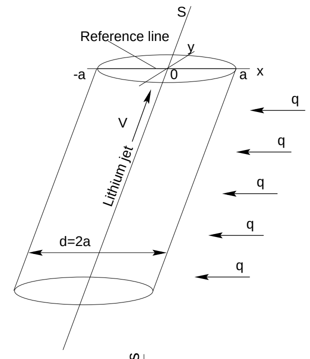
$$\Delta T_{max} = \alpha q_{pol} \sqrt{\frac{4 t_{transit}}{\pi \kappa \rho c_p}}, \qquad (4.16)$$

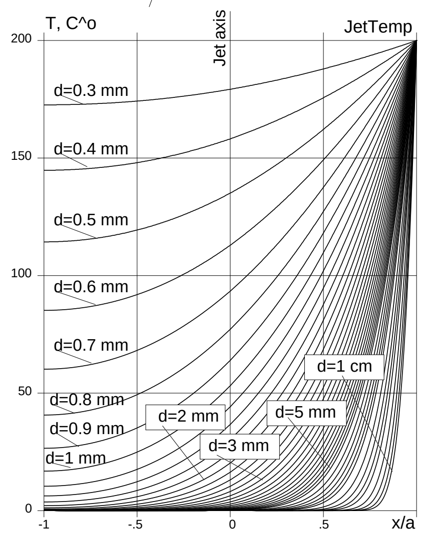



*Power extraction by the jets of LiLi in the X-point region in tokamaks.*

# Summary on jets

**Jets in the divertor region are not suitable for the power extraction**

***At the same time, jets along the magnetic field at the side surface of the tokamak plasma could be an attractive option:***

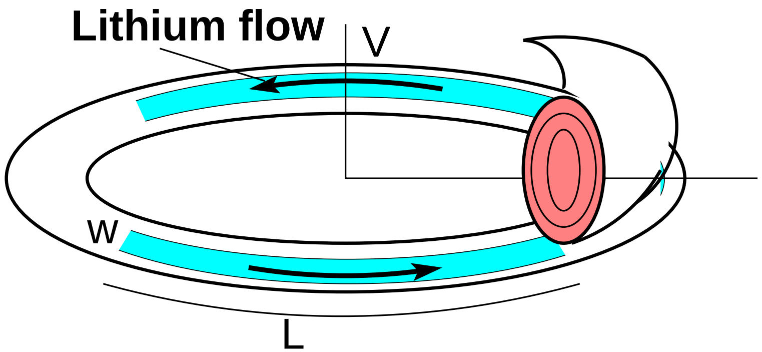
1. ***No leading edge effect;***
2. ***No problem with close loop: jet can penetrate into the toroidal field and get out it;***
3. ***Can intercept the outstanding first orbit $\alpha$-particles.***

***The "sausage" surface tension instability remains the issue.***

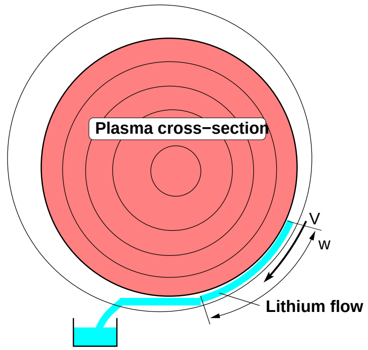
*Still the use of jets are much more complicated than the thin LiLi layer at the top of a heat sink.*

# 5 Flowing LiLi system for HT-7

***Two options are discussed for HT7***




***toroidal flow initiated by the LiLi injection***




***poloidal flow driven by gravity***

*The reference sufficient velocity is based on thickness $\delta$ of the diffusion layer*

$$\frac{dN}{dt}=\frac{10^{22}}{s},\quad V_{pol,cm/s}=\frac{2_{cm^3/s}}{\delta_{cm}\cdot L_{cm}},\quad V_{tor,cm/s}=\frac{2_{cm^3/s}}{\delta_{cm}\cdot W_{\delta,cm}}. \tag{5.1}$$

*Without mixing*

$$\delta_{cm}\simeq\sqrt{D\Delta t},\quad \delta_{pol,cm}=\delta_{tor,cm}=\frac{10^{-4}}{2}W_{cm}L_{cm}=0.05\frac{W_{cm}}{10_{cm}}\frac{L_{cm}}{100_{cm}}. \tag{5.2}$$

***Poloidal option requires about ten times smaller velocity***

$$V_{pol,cm/s}=\frac{0.4}{\frac{W_{\delta,cm}}{10_{cm}}\frac{L^2_{cm}}{100^2_{cm}}},\quad V_{tor,cm/s}=\frac{4}{\frac{W^2_{\delta,cm}}{10^2_{cm}}\frac{L_{cm}}{100_{cm}}}. \tag{5.3}$$

*Magnetic Reynolds number for*

1. *toroidal option*

$$\mathcal{R}_{0,tor}^{LiLi} \simeq 4L_m V_{tor,m/s} = \frac{1.6 \cdot 10^{-1}}{\frac{W_{\delta,cm}^2}{10_{cm}^2}}. \qquad (5.4)$$

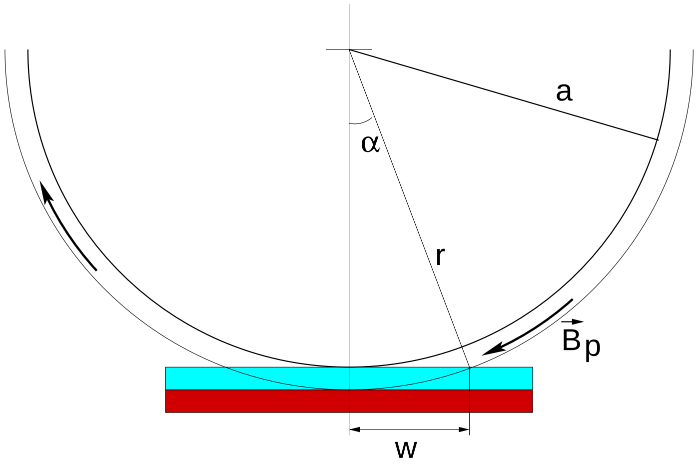
2. *poloidal option*

$$\Re_{0,pol}^{LiLi} \simeq 4W_m V_{pol,m/s} = \frac{1.6 \cdot 10^{-3}}{\frac{L_{cm}^2}{100_{cm}^2}} \qquad (5.5)$$

***For poloidal flow*** $\mathcal{R}_{0,pol}^{LiLi} = 0.01\mathcal{R}_{0,tor}^{LiLi}$***. All MHD effects are minimal***

# 5.1 Concerns with toroidal flow

**Toroidal flow has complicated and unpredictable interaction with the tokamak magnetic field**




$$\tan\alpha = \frac{w}{a}, \quad B_n = B_p(r)\sin\alpha = B_p(a)\frac{aw}{r^2} \tag{5.6}$$

*Pressure drop due to* $B_n$

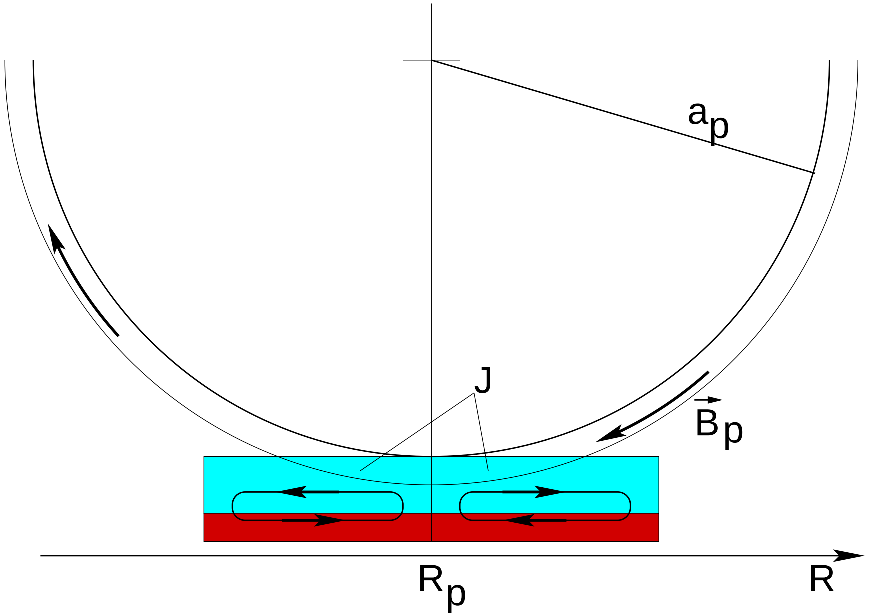
$$\begin{aligned} B_p &= \frac{aB_{tor}}{Rq} \simeq \frac{B_{tor}}{12} \simeq \frac{1}{6}\frac{B_{t,T}}{2_T}, \\ \Delta^{(\mathrm{J}\times\mathrm{B})} p_{MPa} &= \mathcal{R}_{0,tor}\frac{B_n^2}{2\mu_0} \\ &\simeq 2\cdot 10^{-4}\cdot\frac{10^2_{cm}}{W^2_{\delta,cm}}\cdot\frac{B_t^2}{2_T^2}\cdot\frac{3^2}{q^2}\cdot\frac{25w^2}{a^2}. \end{aligned} \tag{5.7}$$

*Poloidal cross-section of the plasma and the flow*

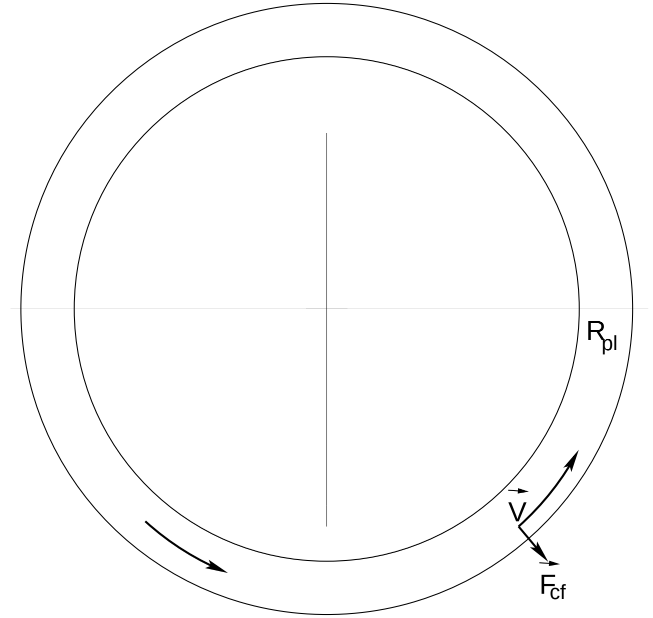
***The pressure drop of the order of $2\cdot 10^{-4}$ MPa can significantly disturb the toroidal flow***

| ***Gravity drive*** | ***External injection drive*** |
|---|---|
| $\Delta H = \frac{3\cdot 10^{-4}_{MPa}\cdot 10^6}{\rho g} = 4\ cm. \quad (5.8)$ | $\rho^{LiLi}\frac{V^2}{2} = 2\cdot 10^{-4}_{MPa}\cdot 10^6, \quad V_{m/sec} > 0.9 \quad (5.9)$ |

**Inhomogeneous in radial (along R ) direction flow velocity drive electric current vortices, which drag the flow in the middle of channel**




*Inhomogeneous in radial (along R ) direction flow velocity drive electric current vortices, which drag the flow in the middle of channel*




*The effect of the centrifugal force is difficult to analyze*

**Because of complications, the toroidal LiLi flow may be impossible in the tokamak magnetic field**

# 5.2 Thin LiLi layer at the top of the heat sink

$$L = 2\ m, \quad W = 0.1\ m \quad P = 0.1\ MW \quad Q = 0.1/0.2 = 0.5\ MW/m^2$$
$$\Delta T = 100^0 \frac{Q}{5\ MW/m^2} h_{mm} = 10^o h_{mm}. \tag{5.10}$$

***Thin 0.1 mm on a heat sink has no issues with heat removal.***

***Small velocity of LiLi is not a concern.***

# 6 Summary



***The development and implementation of the LiWall Fusion regime for tokamaks has a reliable reference option, i.e.,***

***a slow (1 cm/s), thin (0.1 mm) LiLi layer at the top of the heat sink***

*The use of flowing LiLi for power extraction **is not vital** for LiWF and represents an unnecessary complication.*

***For HT-7 (a pioneer device in flowing LiLi) the recommendation could be:***

1. ***Toroidal flow*** *is relatively simple, but has a lot of issues. It can be used as a first step in implementation of LiLi replenishment between plasma shots and as a transition to*
2. ***Poloidal flow of a thin LiLi layer which has multiple advantages:***
   (a) *The Reynolds number is negligible.*
   (b) *Flow can be developed without use of magnetic field (on the workbench)*
   (c) *Flow thickness is in the sub-millimeter range.*

   ***The side walls are not necessary***

   (d) *Flow velocity is in sub-centimeter/sec range.*
   (e) *Flow rate for LiLi replenishment is miniscule (2 $cm^3$/s)*
   (f) *Flow dynamics is dominated by viscous effects.*
   (g) *Except unknowns related to the currents from the plasma to the flow, the flow is predictable. Viscosity can protect the flow from unknown effects.*

***Poloidal option is consistent with major requirements for the flowing LiLi systems for existing stationary tokamaks and for the next step devices.***