Pellet core fueling in tokamaks, stellerators and reversed field pinches

Eleonore Geulin, Bernard Pégourié

DE LA RECHERCHE À L'INDUSTRIE

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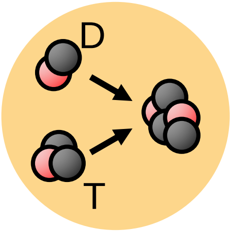
www.cea.fr

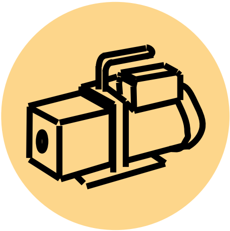
10/11/2022 - AAPPS conference

Introduction - Necessity of fuelling

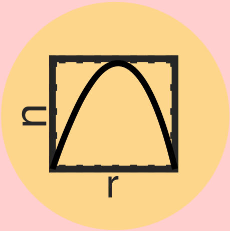
<u>We need to fuel to compensate :</u>



Fusion reactions



Ash pumping



Keep core density

→ balancing outgoing flows

Introduction - Different options for fuelling

Gaz puff injection

✓ easy to use

✗ Fuel only the edge of the plasma

➔ Screening of neutrals in the SOL

Neutral beam injection

✓ Deep penetration

✗ - Power & Matter injection

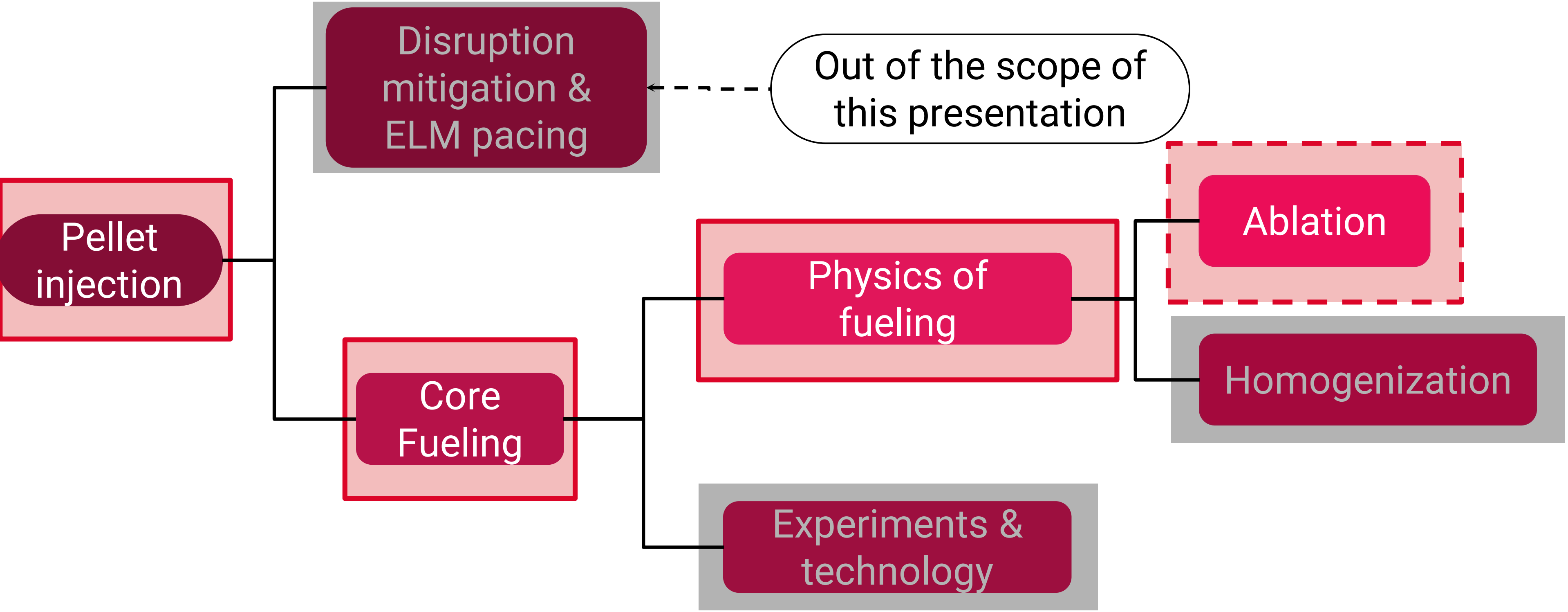
- Not enough fueling for required power

Pellet injection

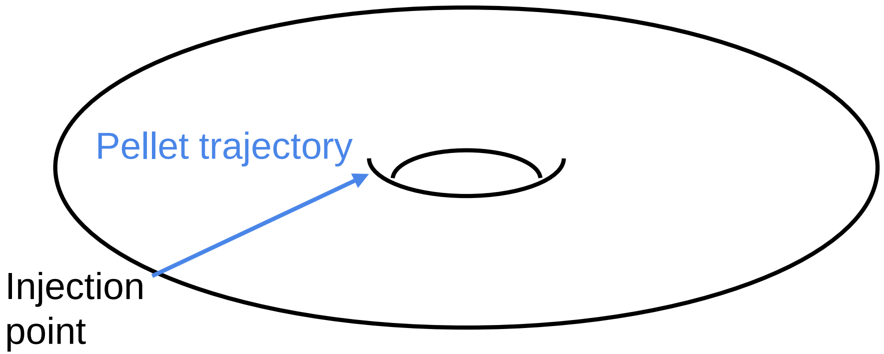
✓ Deep penetration

Efficient fuelling with no momentum or power injection

Physics of fueling : Homogenization explanation



Physic of ablation - Time story of a pellet immersed in plasma



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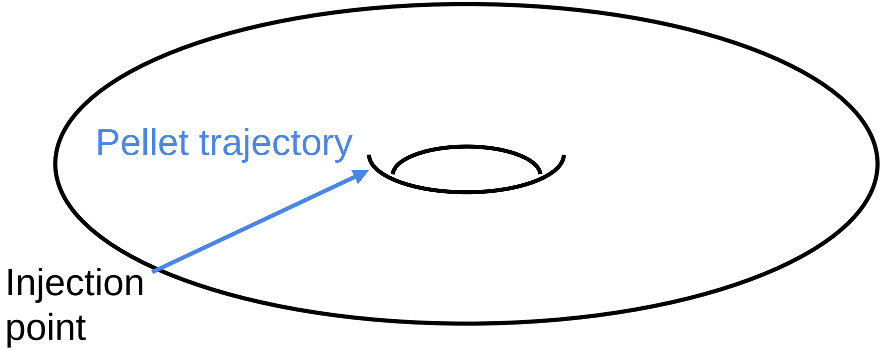
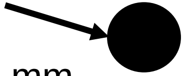
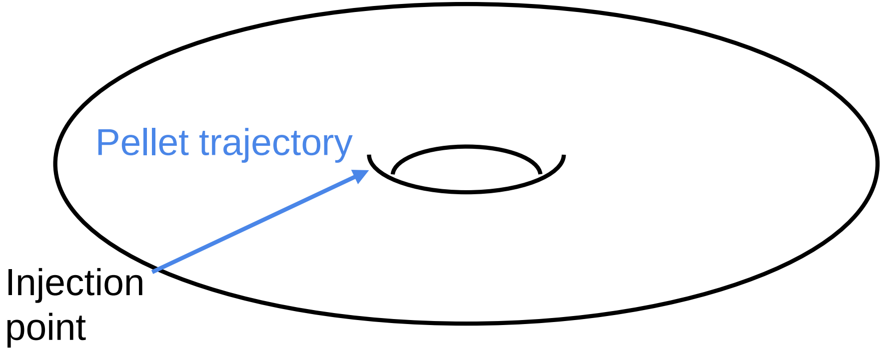


Pellet

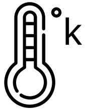


D ~ 1 mm
T° ~ 15K
V ~ 200 m/s to a few km/s

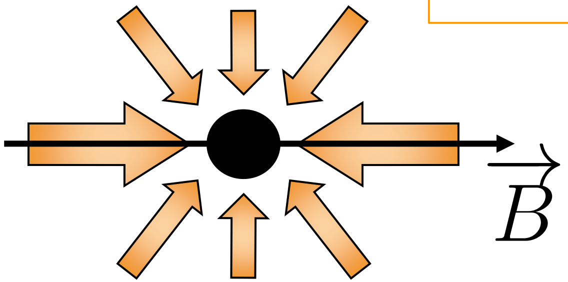
Physic of ablation - Time story of a pellet immersed in plasma



- By heating the pellet,

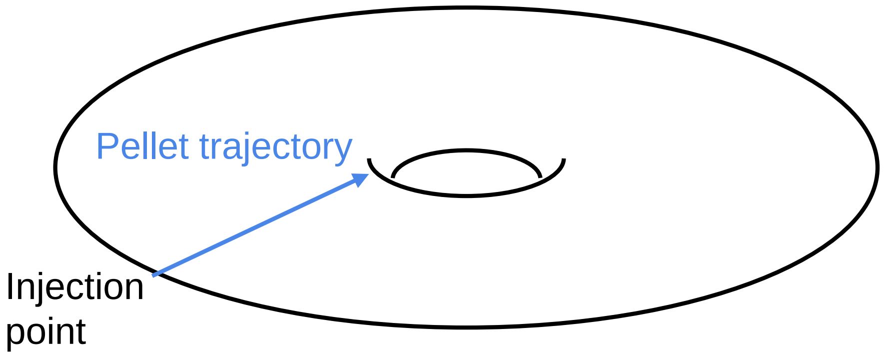


Plasma Heat flux

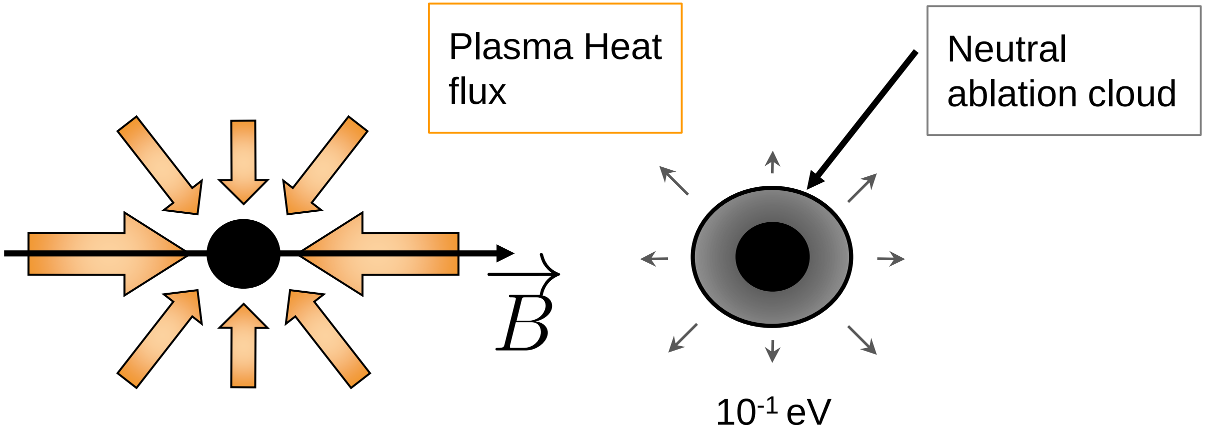


ablation : Loss of a material caused by vaporization

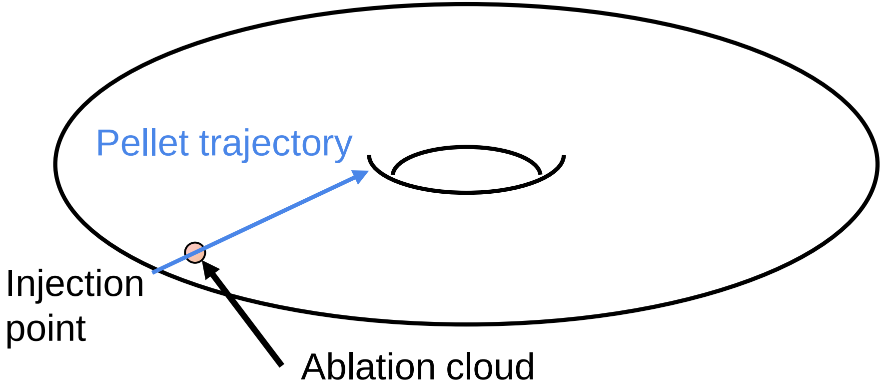
Physic of ablation - Time story of a pellet immersed in plasma



- <u>By heating the pellet,</u>
  ⇒ Neutral ablation cloud

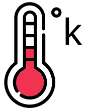


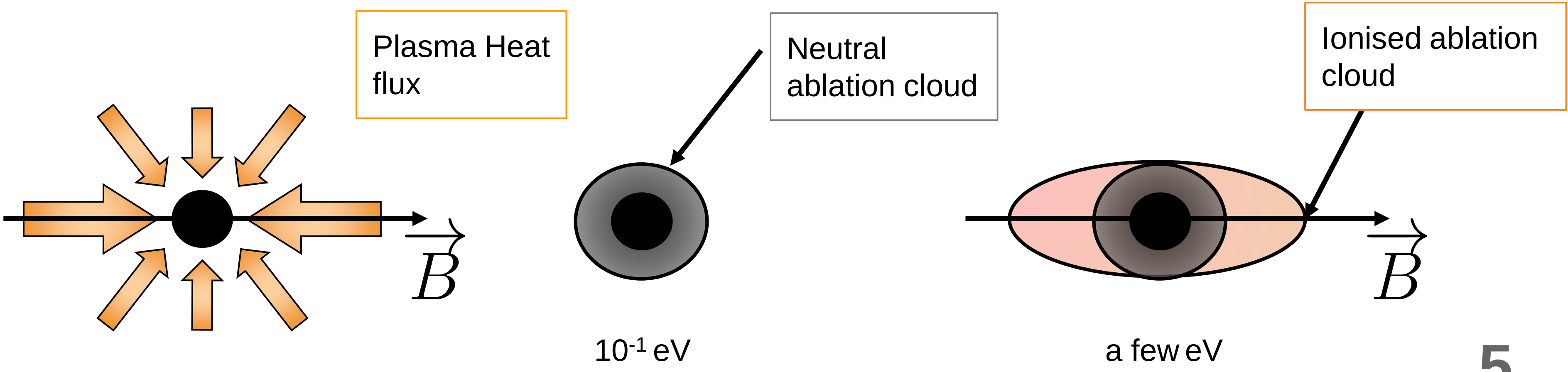
Physic of ablation - Time story of a pellet immersed in plasma



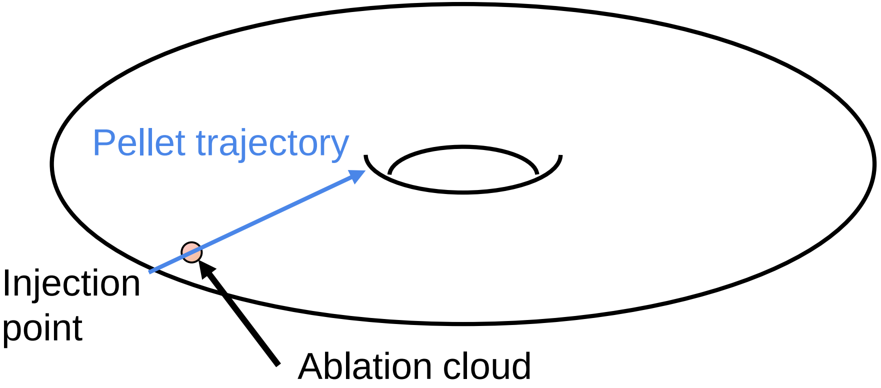
- <u>By heating the pellet,</u>
  ⇒ Neutral ablation cloud

  ⇒ Ionized ablation cloud

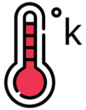




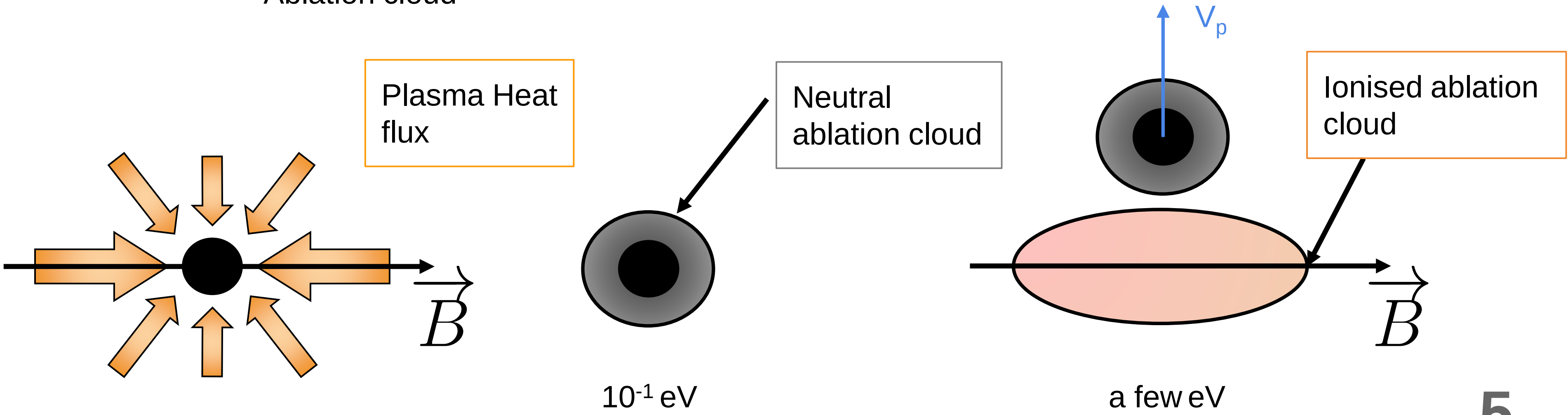
Physic of ablation - Time story of a pellet immersed in plasma



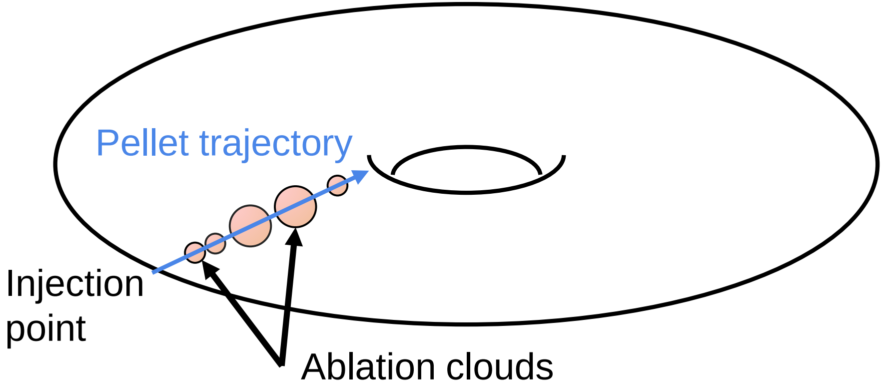
- <u>By heating the pellet,</u>
  - ⇒ Neutral ablation cloud
  - ⇒ Ionised ablation cloud



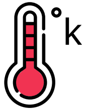
- <u>Ionised ablation cloud separate from neutral part (cloud + pellet),</u>



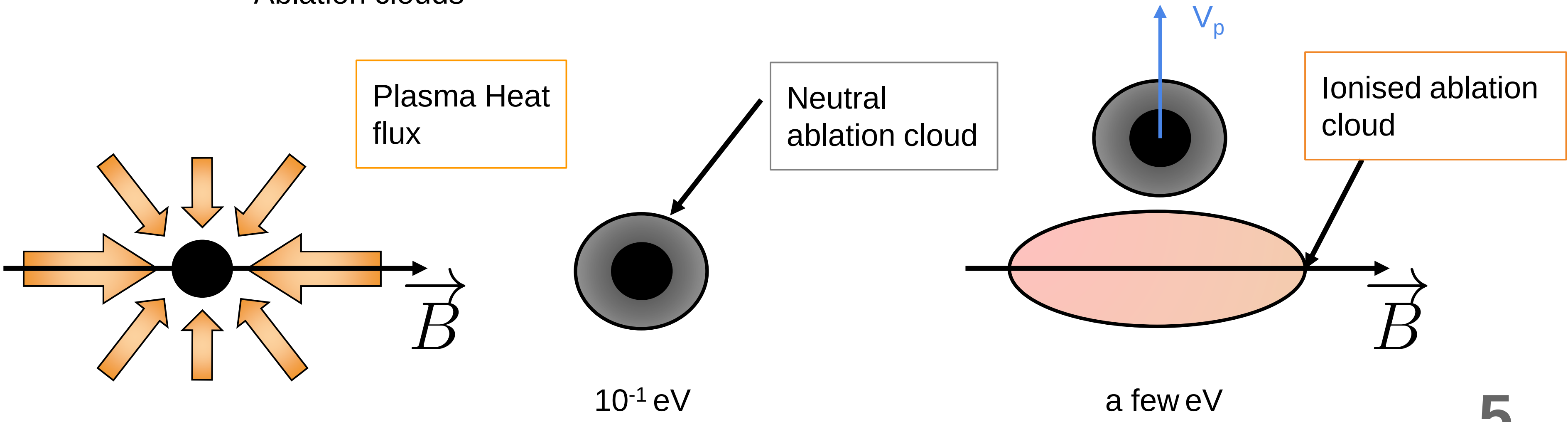
Physic of ablation - Time story of a pellet immersed in plasma



- By heating the pellet,
  ⇒ Neutral ablation cloud
  ⇒ Ionised ablation cloud



- Ionised ablation cloud separate from neutral part (cloud + pellet),
  ⇒ Happens all along the pellet path



Pellet penetration (L_p) depends mainly on the plasma temperature

Plasma density / temperature

Pellet penetration length :

$$L_p \propto V_{pellet} N_{pellet}^{1/2} n_{plasma}^{-1/3} T_{plasma}^{-5/3}$$

Pellet velocity / particle contents

2 conclusions :

⇒ Temperature dependance is the more limiting for penetration

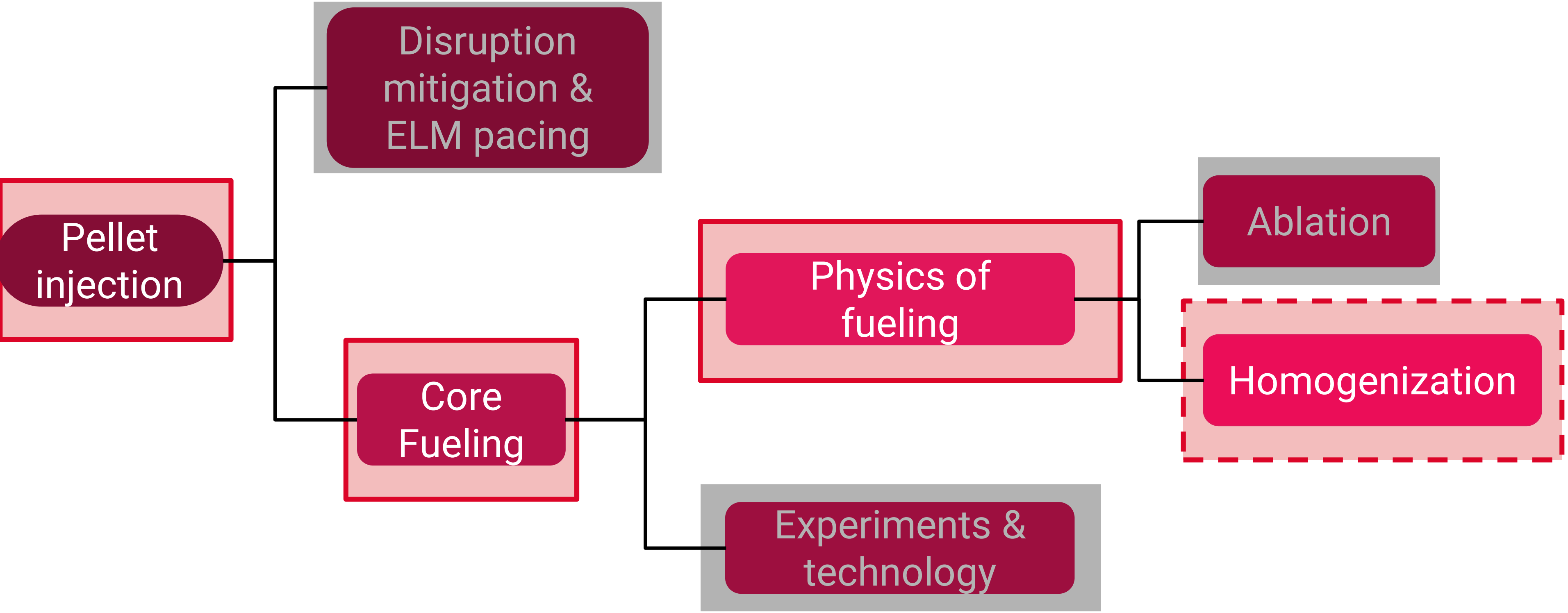
⇒ Increase V_p more efficient than N_p to increase L_p

Pellet Lp : from 20% to >50% plasma radius in present day tokamaks

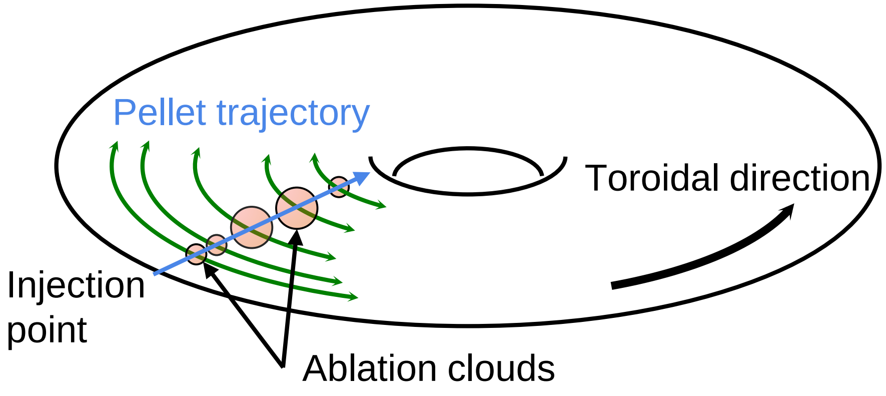
Fast ions (ICRH,NBI) moderate ablation increase

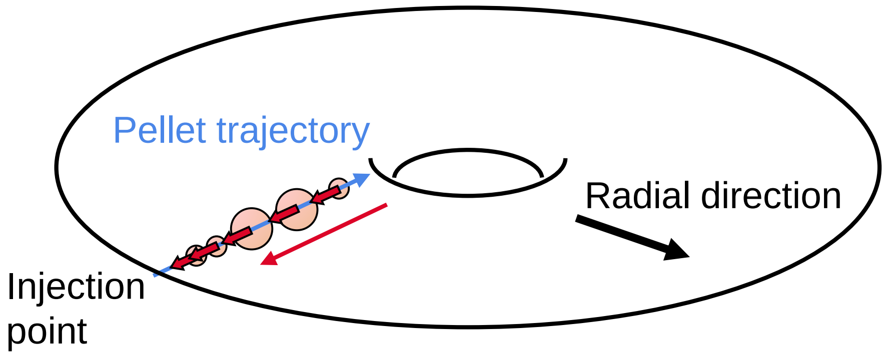
Fast electrons (ECRH) significant ablation increase; (LHCD) pellet mass sublimation

Physics of fueling : Homogenization explanation



During homogenization phase deposed matter moves on the parallel and radial direction

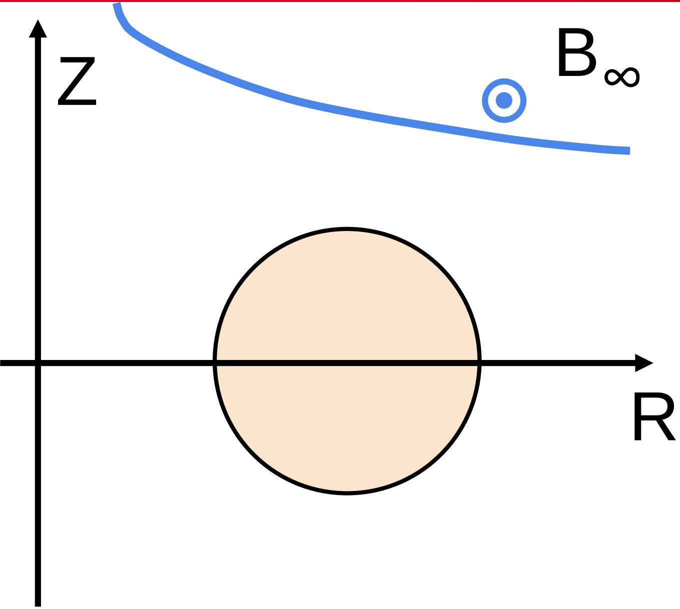


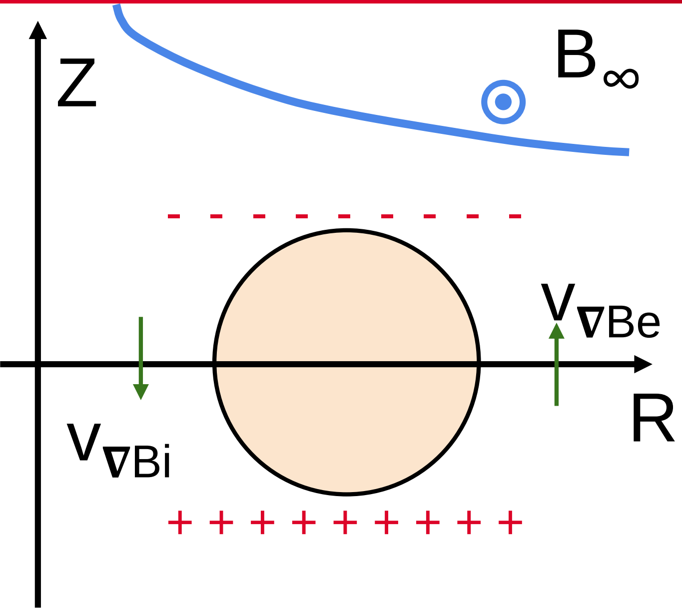


- Homogenization : deposited matter leads to a new axisymmetric density and temperature profiles

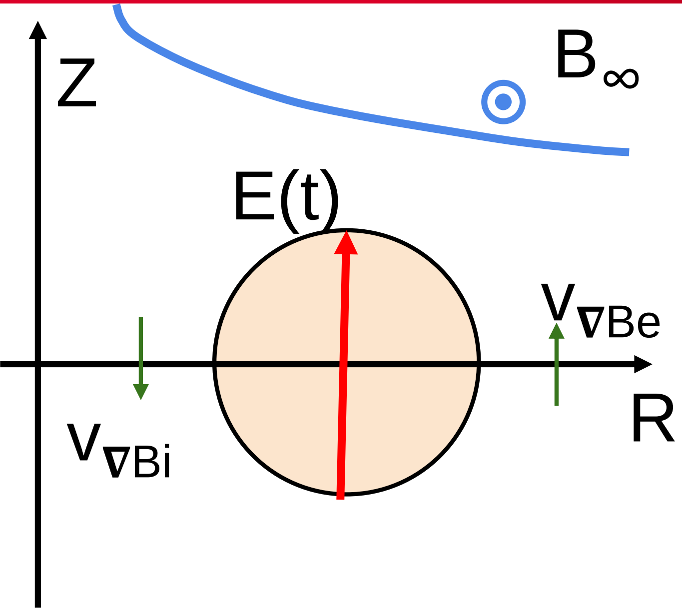
- Deposed matter displacement :
  - ⇒ Parallel expansion
  - ⇒ Radial drift (down ∇B direction)

Physic of Homogenization : Cloud immersed in magnetic field gradient



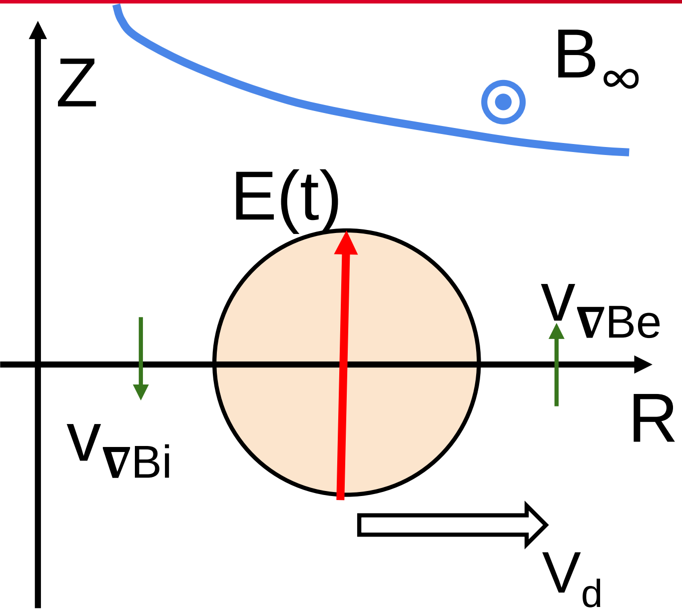


$\mathbf{v}_{\nabla Be,i}$: Vertical e^-, i^+ drift



$\mathbf{v}_{\nabla Be,i}$: Vertical e^-, i^+ drift

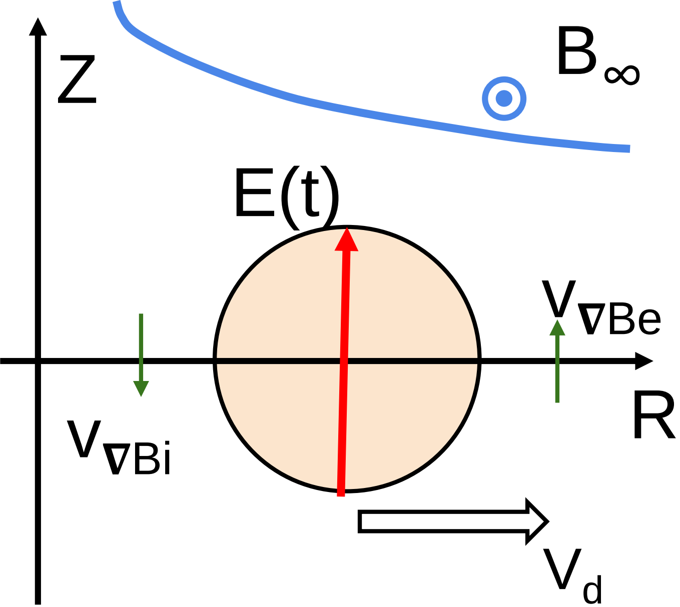
Physic of Homogenization : Drift velocity appears



$\mathbf{v}_{\nabla Be,i}$: Vertical e^-, i^+ drift

$$V_d = \frac{E \times B_\infty}{B_\infty^2}$$

Physic of Homogenization : Acceleration induced is depending on the pressure difference



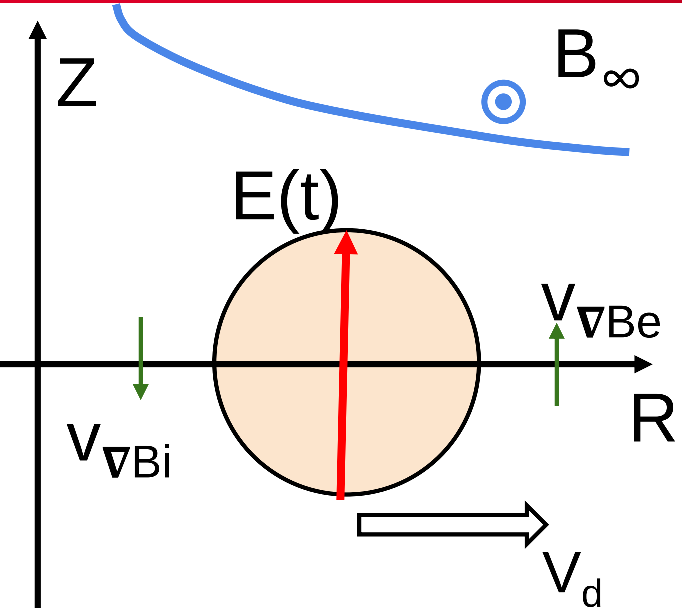
$\mathbf{v}_{\nabla Be,i}$: Vertical e^-, i^+ drift

$$V_d = \frac{E \times B_\infty}{B_\infty^2}$$

We can calculated the drift acceleration :

$$\frac{dV_d}{dt} = \frac{2(p_0 - p_\infty)}{n_0 m_0 R_c}$$

p_0 : Ionised cloud pressure
p_∞ : Background plasma pressure
n_0 : Ionised cloud density
m_0 : Ionised cloud mass
R_c : Curvature radius



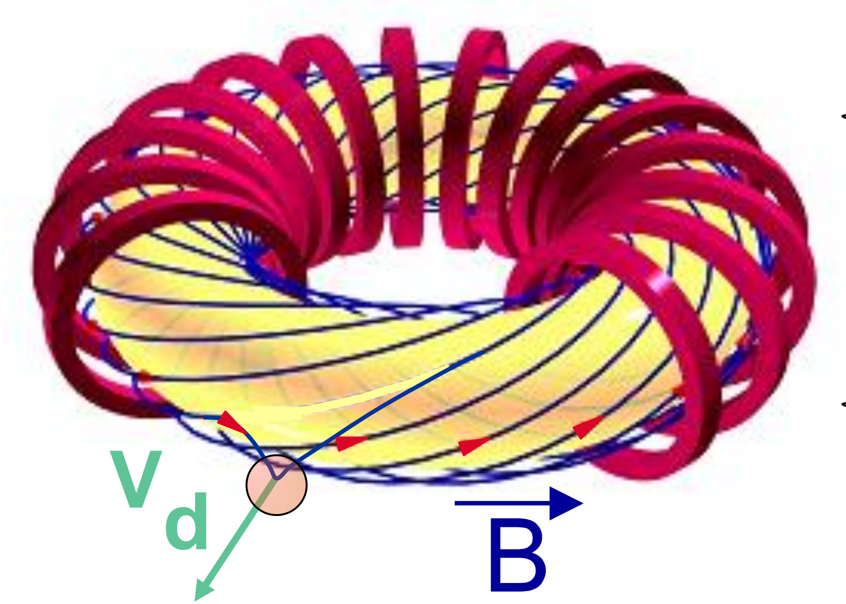
$\mathbf{v}_{\nabla Be,i}$: Vertical e^-, i^+ drift

$$V_d = \frac{E \times B_\infty}{B_\infty^2}$$

We can calculated the drift acceleration :

$$\frac{dV_d}{dt} = A_{\nabla B}$$

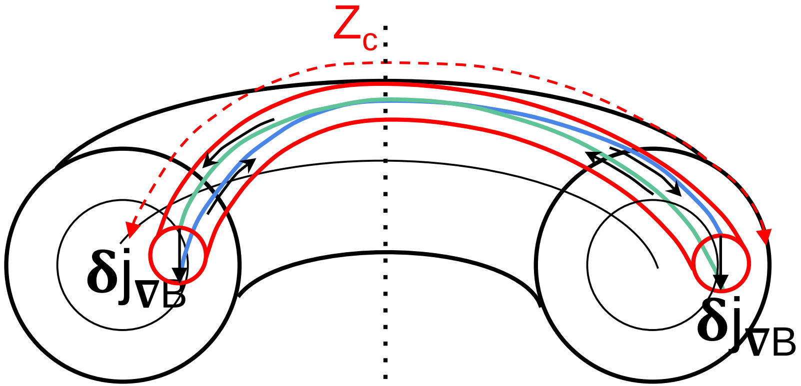
Physic of Homogenization - Cloud drags magnetic flux tube it intercepts



- Ideal MHD :
  <u>**Cloud drags magnetic flux tube**</u>

- Rotational transform, winding of the field line
  ⇒ Drift damping by 2 phenomena

1st damping term from Internal Connection - Cloud long enough for field lines connecting charged part of the cloud

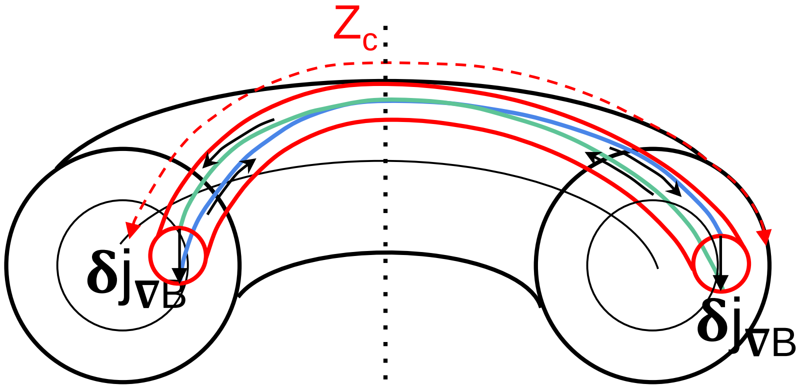


[Rozhansky 2005]

- Critical length Z_c reach

  → drift current circuit is closed inside the cloud

1^{st} damping term from Internal Connection - Cloud long enough for field lines connecting charged part of the cloud

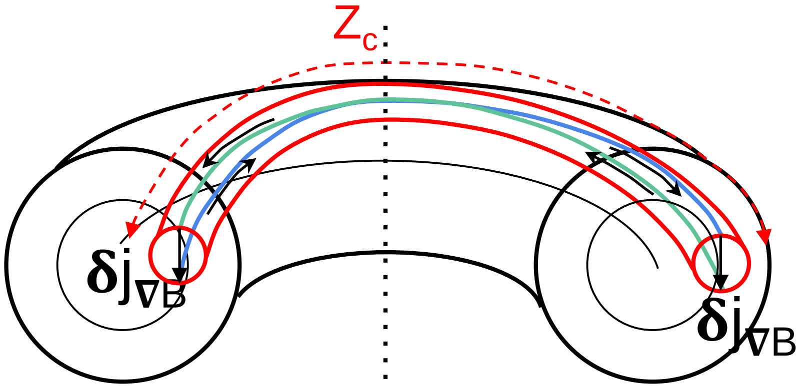


[Rozhansky 2005]

$$\frac{d\mathbf{V}_d}{dt} = A_{\nabla B} D_{\mathrm{IC}}$$

1^{st} damping term
→ **I**nternal **C**onnection

1st damping term from Internal Connection - Cloud long enough for field lines connecting charged part of the cloud



[Rozhansky 2005]

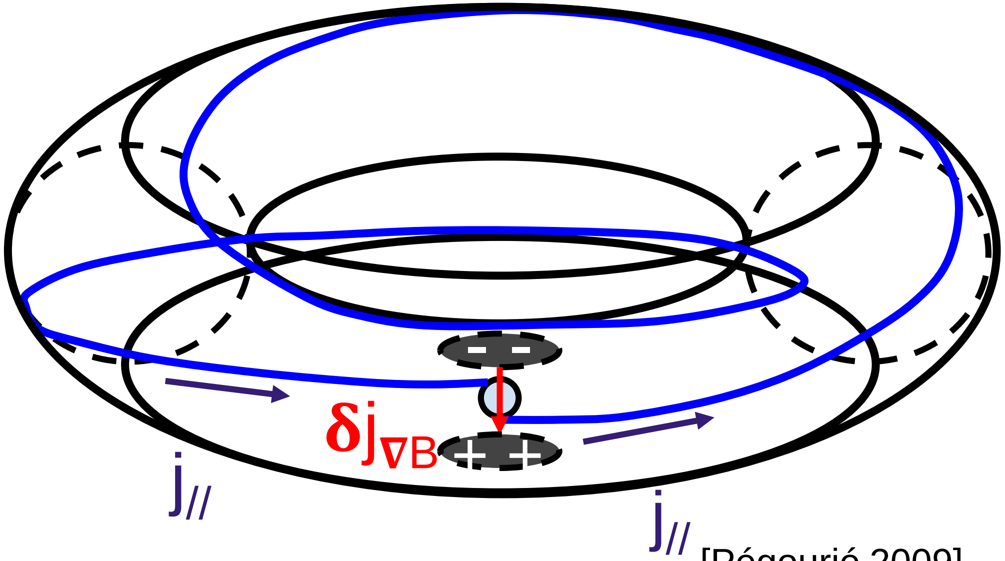
$$\frac{d\mathbf{V}_d}{dt} = A_{\nabla B} D_{\mathrm{IC}} \quad \propto \mathcal{H}(Z_c - Z_0)$$

1st damping term
→ **I**nternal **C**onnection

Z_c : Critical length where the relative current are inverted
Z_0 : Cloud length

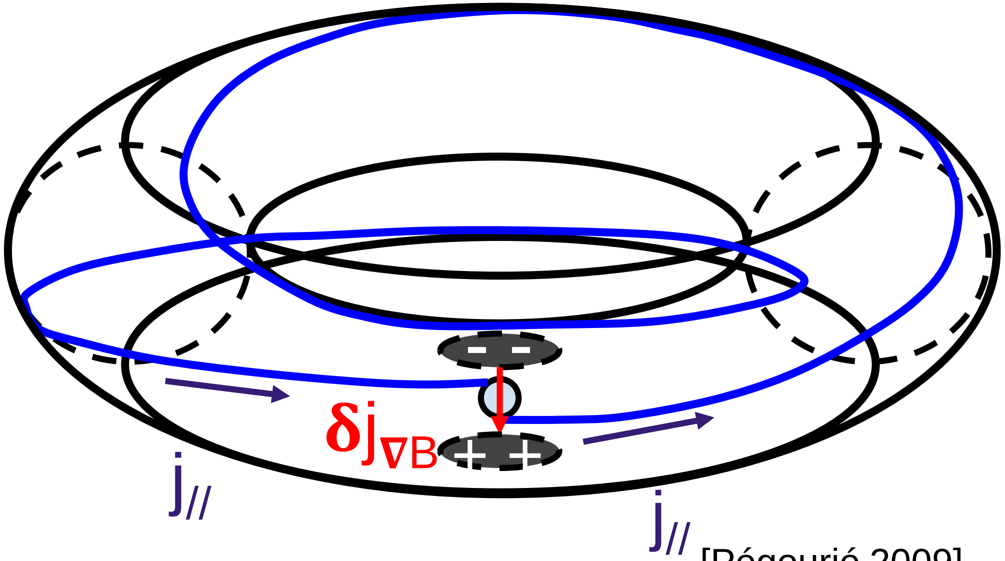
2nd damping term from External Connection - perturbed flux tube connects charged part of the cloud

Parallel currents flow along field lines
→ closing drift current



[Pégourié 2009]

2^{nd} damping term from External Connection - perturbed flux tube connects charged part of the cloud

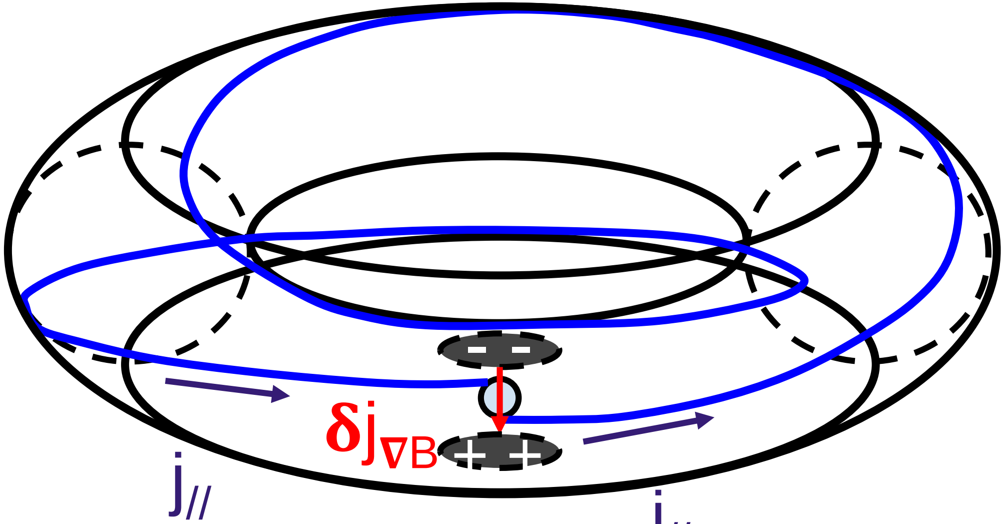


[Pégourié 2009]

$$\frac{d\mathbf{V}_d}{dt} = A_{\nabla B} D_{\mathrm{IC}} - D_{\mathrm{EC}}$$

- 2^{nd} damping term
  → **E**xternal **C**onnection

2nd damping term from External Connection - perturbed flux tube connects charged part of the cloud



[Pégourié 2009]

σ_∞ : Parallel conductivity

Z_∞ : Length of the connecting flux tube

$$\frac{d\mathbf{V}_d}{dt} = A_{\nabla B} D_{\mathrm{IC}} - D_{\mathrm{EC}}$$

$$\propto V_d \frac{\sigma_\infty B_\infty^2}{Z_\infty}$$

2nd damping term
→ **E**xternal **C**onnection

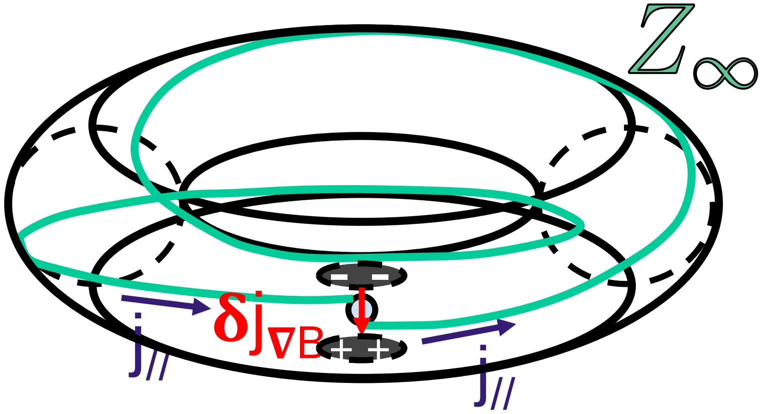
Damping of the cloud drift phase

$$\frac{d\mathbf{V}_d}{dt} = A_{\nabla B} D_{\mathrm{IC}} - D_{\mathrm{EC}}$$

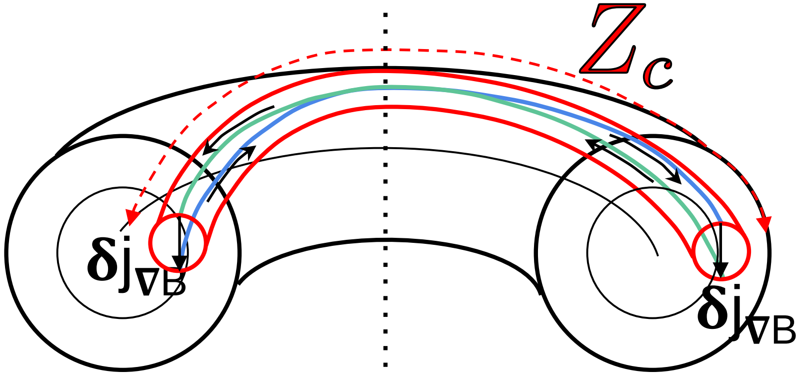
$$\frac{d\mathbf{V}_d}{dt} = A_{\nabla B} D_{\mathrm{IC}} - D_{\mathrm{EC}}$$

How D_{EC} & D_{IC} influence the deposition profile for different magnetic configuration ? (tokamak/Stellarator/RFP)

Competition between D_{EC} & D_{IC} - in a tokamak the external connection is the dominant effect



$$\tau_{EC} \sim \frac{Z_\infty}{C_A}$$



$$\tau_{IC} \sim \frac{Z_c}{C_s}$$

τ : efficient time

$C_A >> C_s$

$Z_\infty > Z_c$

More efficient close to a rational q

Competition between D_{EC} & D_{IC} - in a tokamak; External Connection is dominant

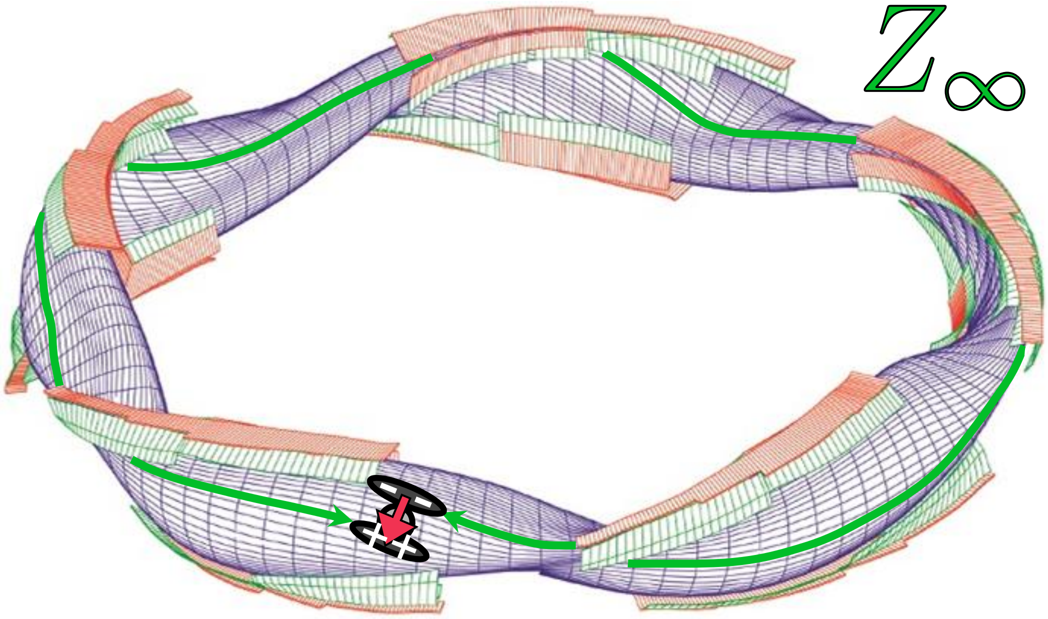
$$\tau_{EC} \sim \frac{Z_\infty}{C_A} < \tau_{IC} \sim \frac{Z_c}{C_s}$$

[Sakamoto 2013]

$\Rightarrow$ External Connection

more efficient for tokamak

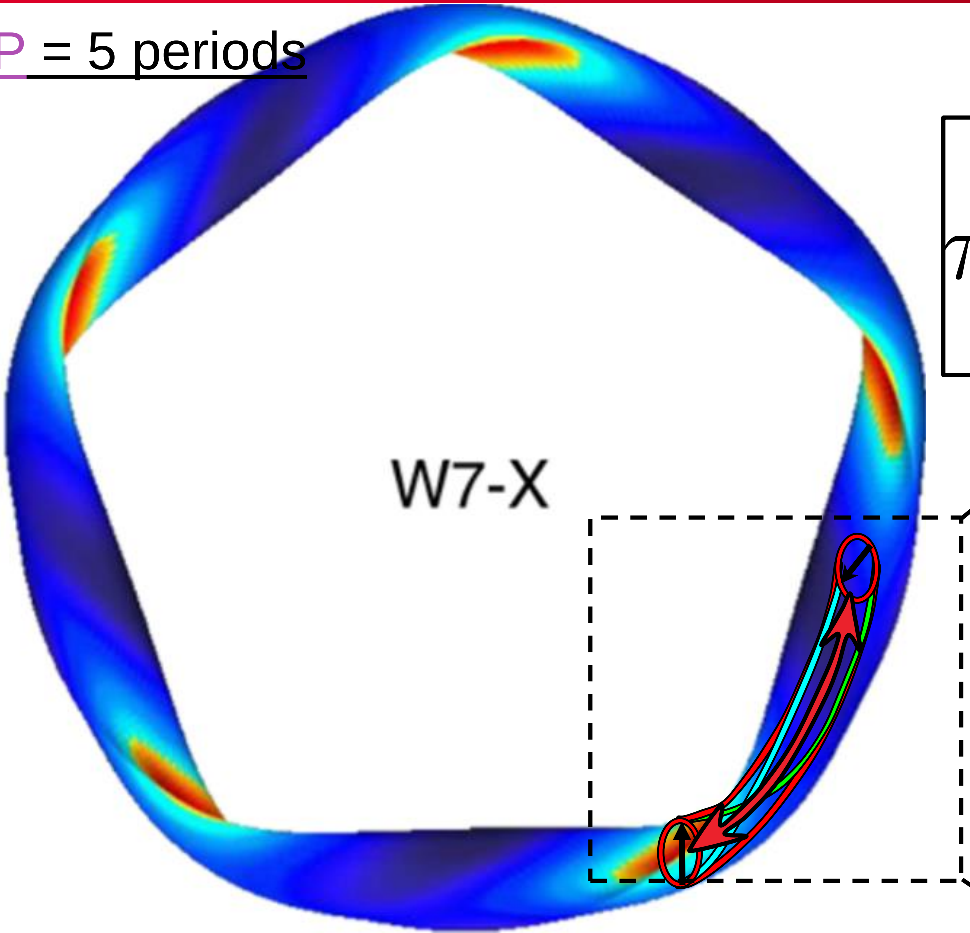
Competition between D_{EC} & D_{IC} - in a stellarator; External Connection



$$\tau_{EC} \sim \frac{Z_\infty}{C_A}$$

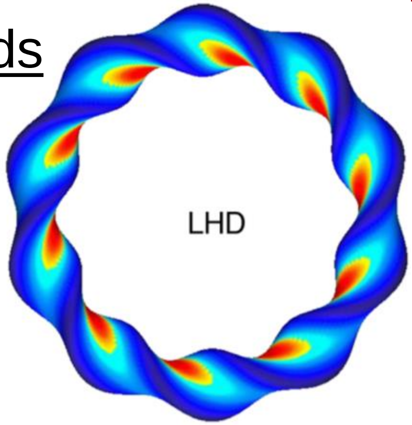
Competition between D_{EC} & D_{IC} - in a stellarator; Internal Connection

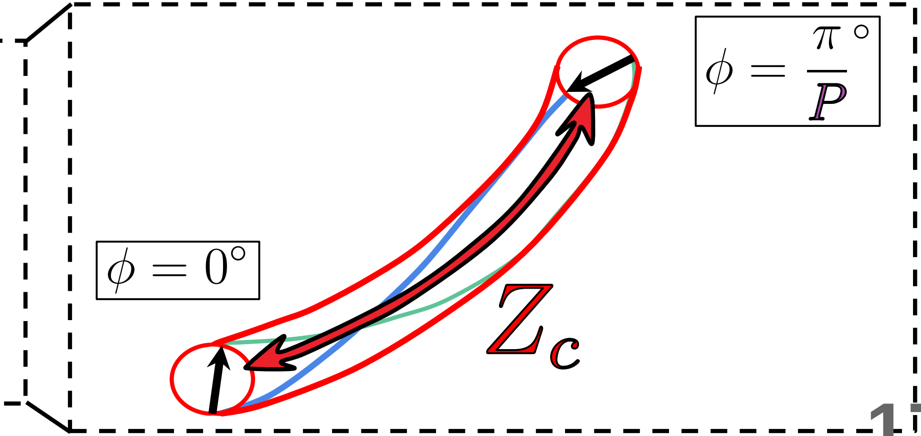
P = 5 periods



P = 10 periods

$$\tau_{IC} \sim \frac{Z_c(P)}{C_s}$$





Competition between D_{EC} & D_{IC} - in a stellarator; Internal Connection is dominant

$$\tau_{EC} \sim \frac{Z_\infty}{C_A} > \tau_{IC} \sim \frac{Z_c(P)}{C_s}$$

[Matsuyama 2012]

⇒ Internal Connection more efficient for stellarator

Drift stops faster in a stellarator than in tokamak

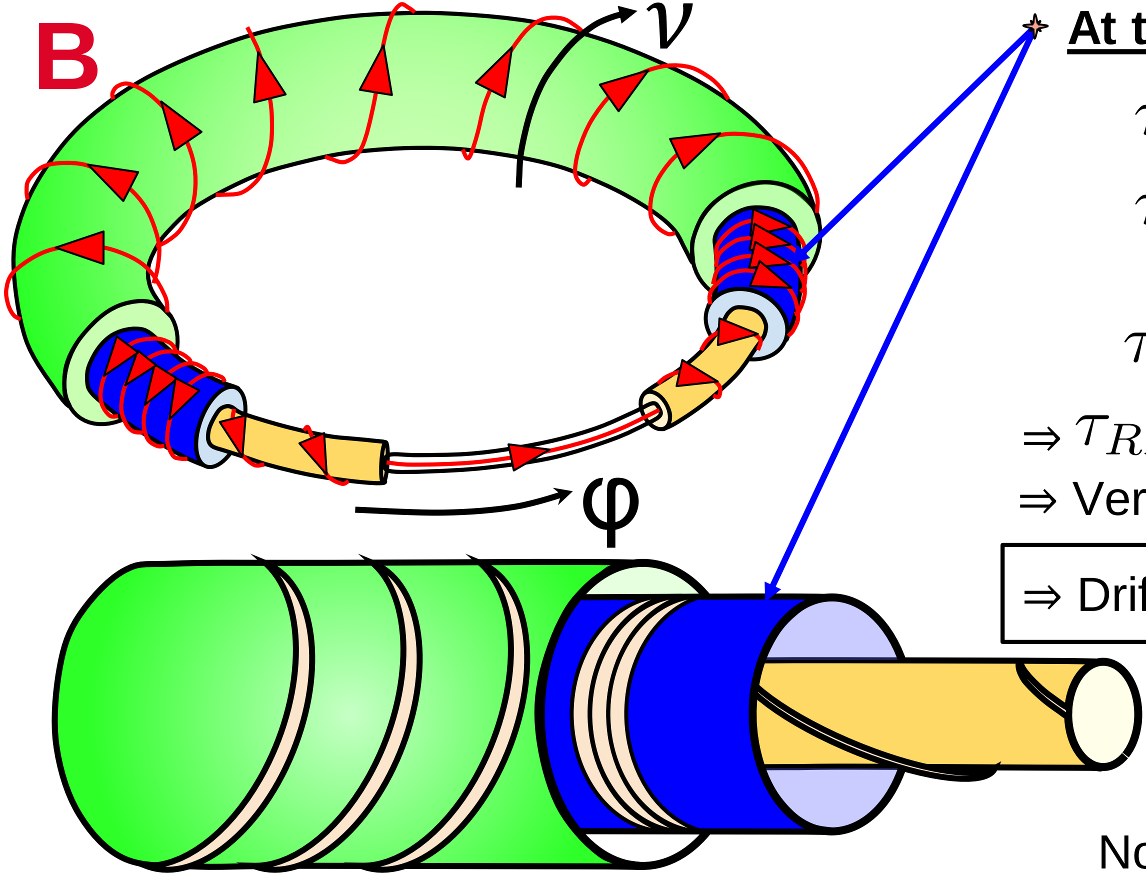
We have :

- τ_{EC} tokamak $\sim \tau_{EC}$ stellarator
- τ_{EC} tokamak $< \tau_{IC}$ tokamak & τ_{EC} stellarator $> \tau_{IC}$ stellarator

Then :

$\Rightarrow \tau_{EC}$ tokamak $> \tau_{IC}$ stellarator

Drift displacement is smaller in a stellarator than in tokamak



At the reversal radius :

$$\left.\begin{aligned} \tau_{Ec} &= \frac{2\pi a}{C_A} \\ \tau_{IC} &= \frac{\pi a}{C_s} \end{aligned}\right\} \tau_{RFP} \propto a$$

$$\neq$$

$$\tau_{\text{tokamak, stellarator}} \propto R$$

$\Rightarrow \tau_{RFP} \ll \tau_{\text{tokamak, stellarator}}$

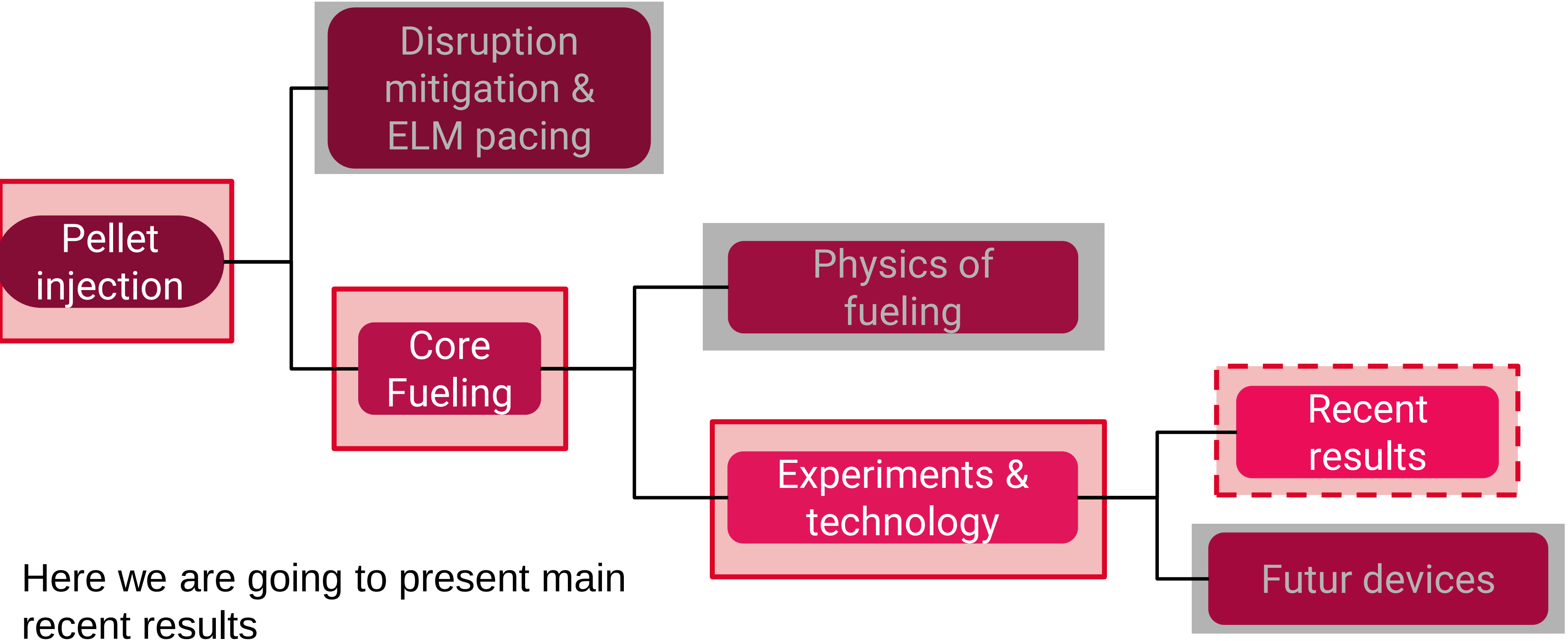
⇒ Very short drift time: magnetic shear

⇒ Drift barrier

[Canton 2000]

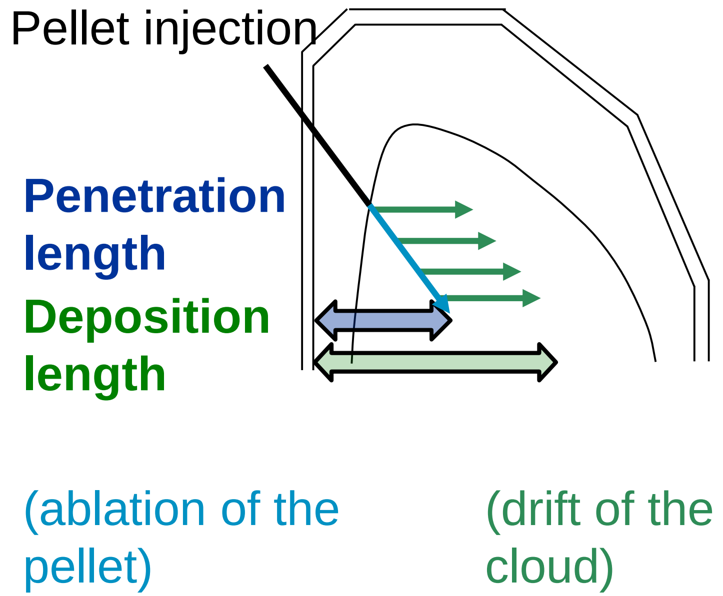
No experiments made yet

Presentation of some results for fueled scenarios



Here we are going to present main recent results
⇒ Similar results on other machines also exist

I - Better fueling from High field side in DIII-D due to the drift of the cloud



- Matter deposition deeper than pellet penetration :
  ⇒ Drift of the cloud

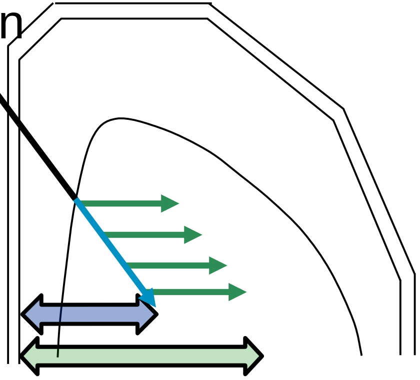
[Baylor 2007]

I - Better fueling from High field side in DIII-D due to the drift of the cloud

Pellet injection

Penetration length

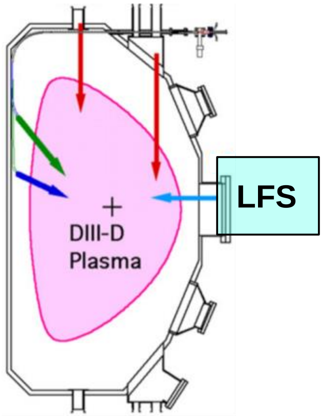
Deposition length

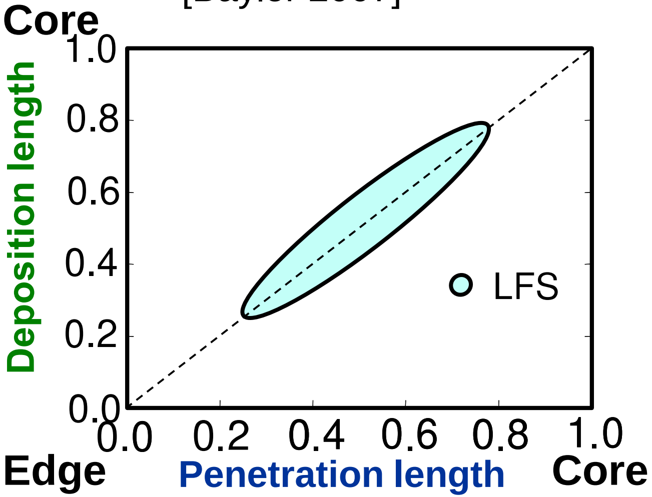


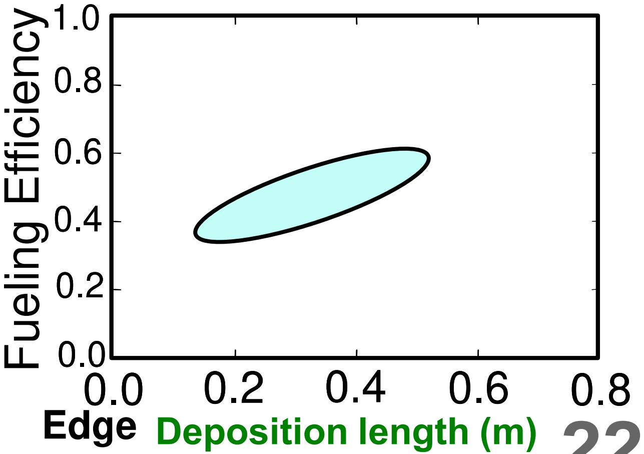
- Matter deposition deeper than pellet penetration :
  ⇒ Drift of the cloud

- Test of different injection points :
  LFS : Deposition ~ penetration

[Baylor 2007]

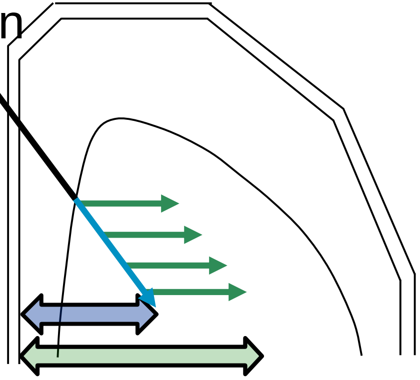






I - Better fueling from High field side in DIII-D due to the drift of the cloud

Pellet injection



Penetration length

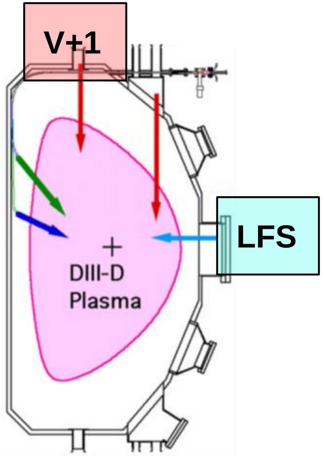
Deposition length

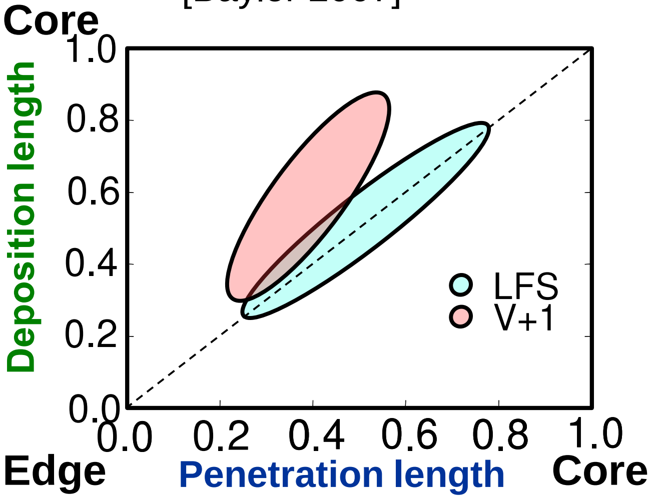
- Matter deposition deeper than pellet penetration :
  ⇒ Drift of the cloud

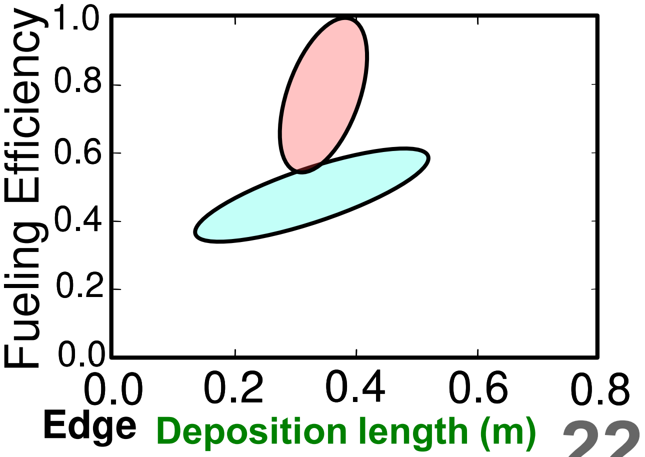
- Test of different injection points :

LFS : Deposition ~ penetration
V+1 : Deposition ~ 2 x deeper than penetration

[Baylor 2007]





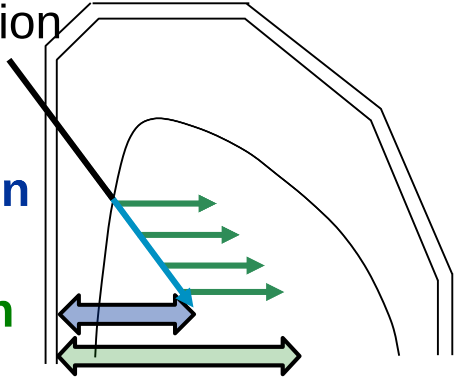


I - Better fueling from High field side in DIII-D due to the drift of the cloud

Pellet injection

Penetration length

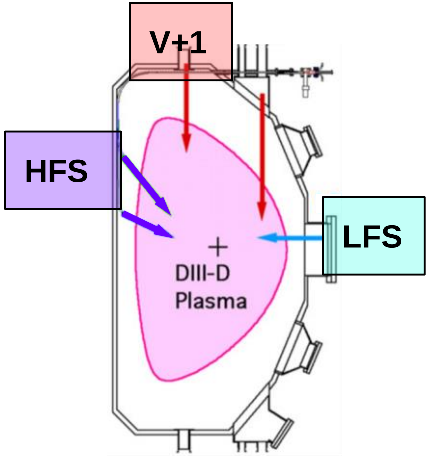
Deposition length

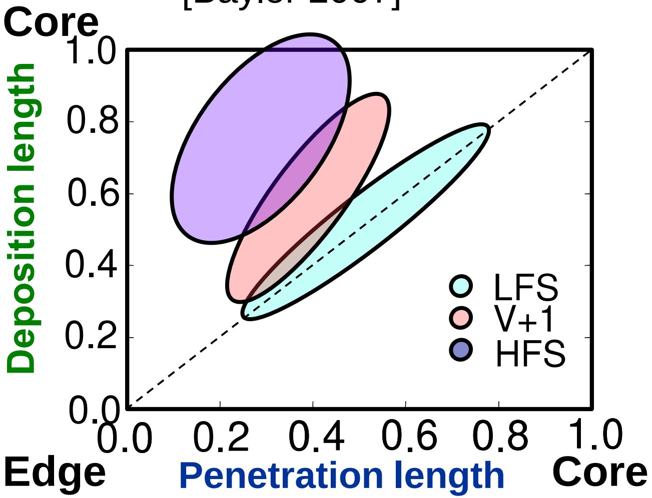


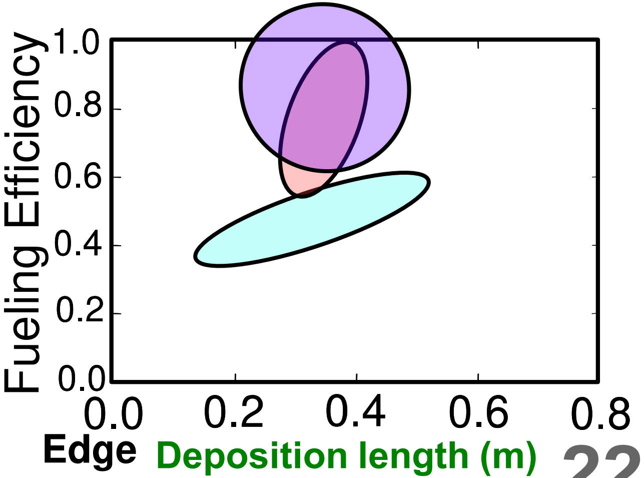
- Matter deposition deeper than pellet penetration :
  - ⇒ Drift of the cloud
- Test of different injection points :

LFS	:	Deposition ~ penetration
V+1	:	Deposition ~ 2 x deeper than penetration
HFS	:	Deposition ~ 4 x deeper than penetration

[Baylor 2007]





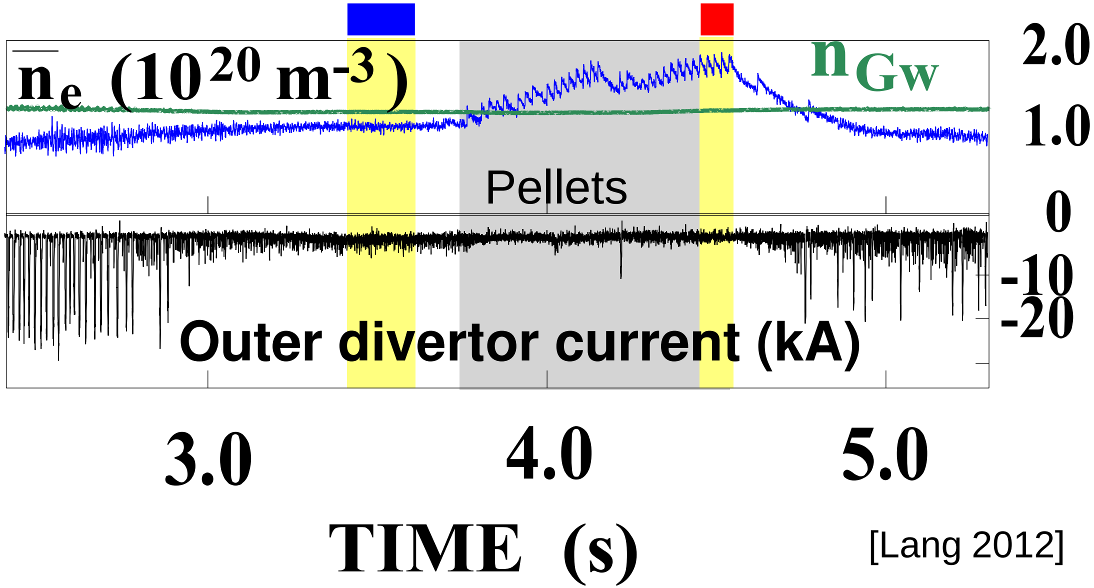


II- Pellet fueling allows RMP ELM suppression above Greenwald density in ASDEX-Upgrade

Tokamak

High density regime (like H mode)

ELMs (self generated or pellet induced)



[Lang 2012]

Resonant Magnetic Perturbation (RMP) + Pellet allowed a density > n_{GW} without ELM

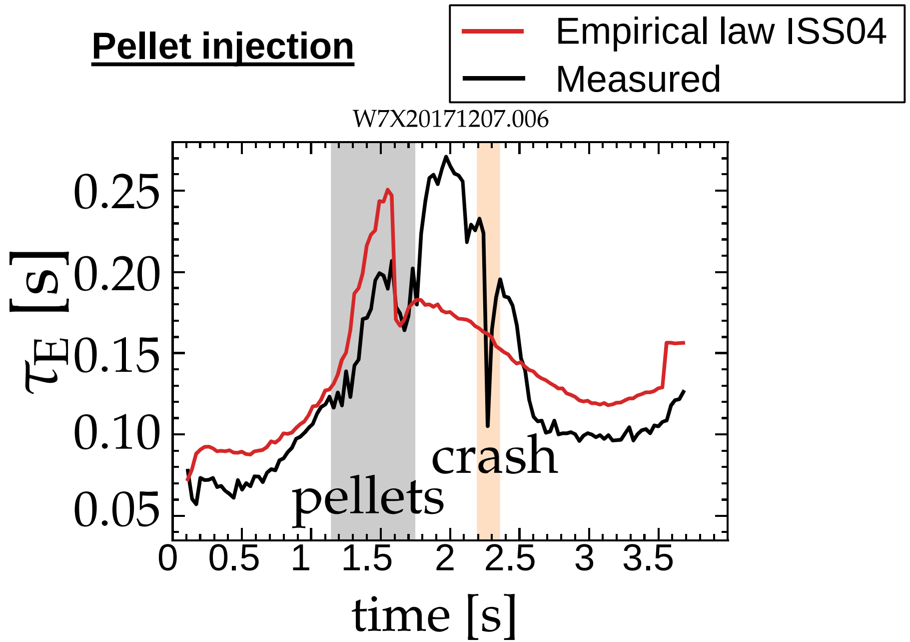
In stellarator, pellet used for density control and improve confinement, ex : LHD and W7-X

Stellarator

- High density regime
- Large confinement time

- Hollow density profile

Pellet injection



[Bozhenkov 2018] [Baldzuhn 2020]

- Pellet increases core density
- Pellet increases global energy confinement time

Presentation of some results for fueled scenarios

- Pellet injection
  - Disruption mitigation & ELM pacing
  - Core Fueling
    - Physics of fueling
    - Experiments & technology
      - Recent results
      - Futur devices

⇒ 4 solutions are developed
- ITER
- JA-DEMO
- EU-DEMO
- Heliotron

Pellet speed limited by the guide tube curvature

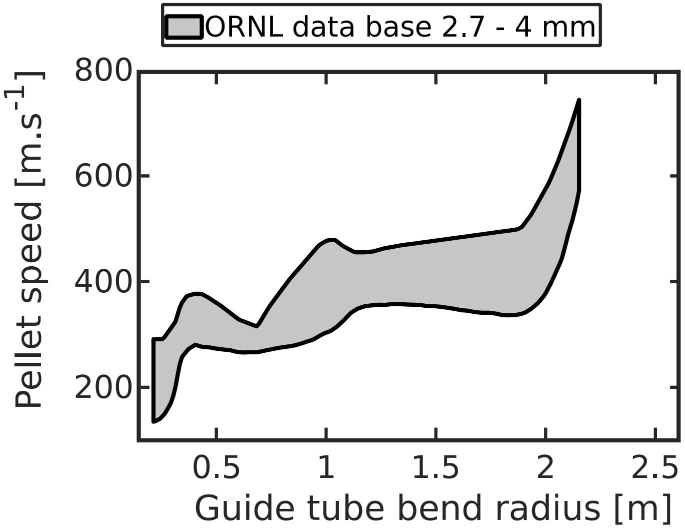
Futur devices will be large

→ Large drift

→ injection from HFS

→ Bended guide tube

→ Limited pellet speed V_p^{Max}



[Poeckl 2021]

R_p (pellet radius) limited by plasma perturbation

Balance to find between R_p & V_p^{Max}
Futur machines take into account pellet injector position

5 fueling system dimensioned :

2 under manufacturing :

- JT-60SA (tokamak)
- ITER (tokamak)

2 as project :

- JA-DEMO (tokamak)
- EU-DEMO (tokamak)

1 preliminary state :

- FFHR (stellarator)

Pellet injector in the future devices

5 fueling system dimensioned :

2 under manufacturing :

- JT-60SA (tokamak)
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Pellet injector in the future devices

<u>5 fueling system dimensioned :</u>

<u>2 under manufacturing :</u>

JT-60SA (tokamak)

ITER (tokamak)

<u>2 as project :</u>

JA-DEMO (tokamak)

EU-DEMO (tokamak)

<u>1 preliminary state :</u>

FFHR (stellarator)

	JT-60SA	ITER	JA-DEMO	EU-DEMO
Fueling rate	≤ 62mg/s	∈ [20,167]mg/s	50mg/s	∈ [42,58]mg/s

Pellet injector in the future devices

5 fueling system dimensioned :

2 under manufacturing :
- JT-60SA (tokamak)
- ITER (tokamak)

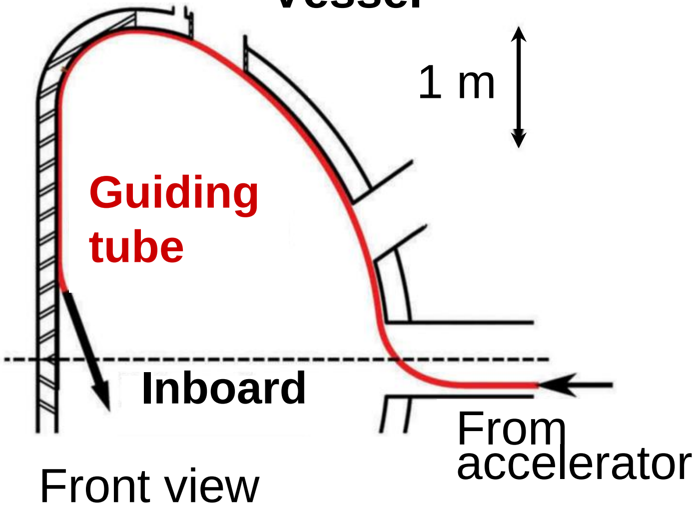
2 as project :
- JA-DEMO (tokamak)
- EU-DEMO (tokamak)

1 preliminary state :
- FFHR (stellarator)

	JT-60SA	ITER	JA-DEMO	EU-DEMO
Fueling rate	≤ 62mg/s	∈ [20,167]mg/s	50mg/s	∈ [42,58]mg/s
Pellet Size	∈ [**1,5**]mg ∈ [**2,3**]mm	**25**mg **5**mm	**17**mg **4**mm	**8**mg **3.4**mm

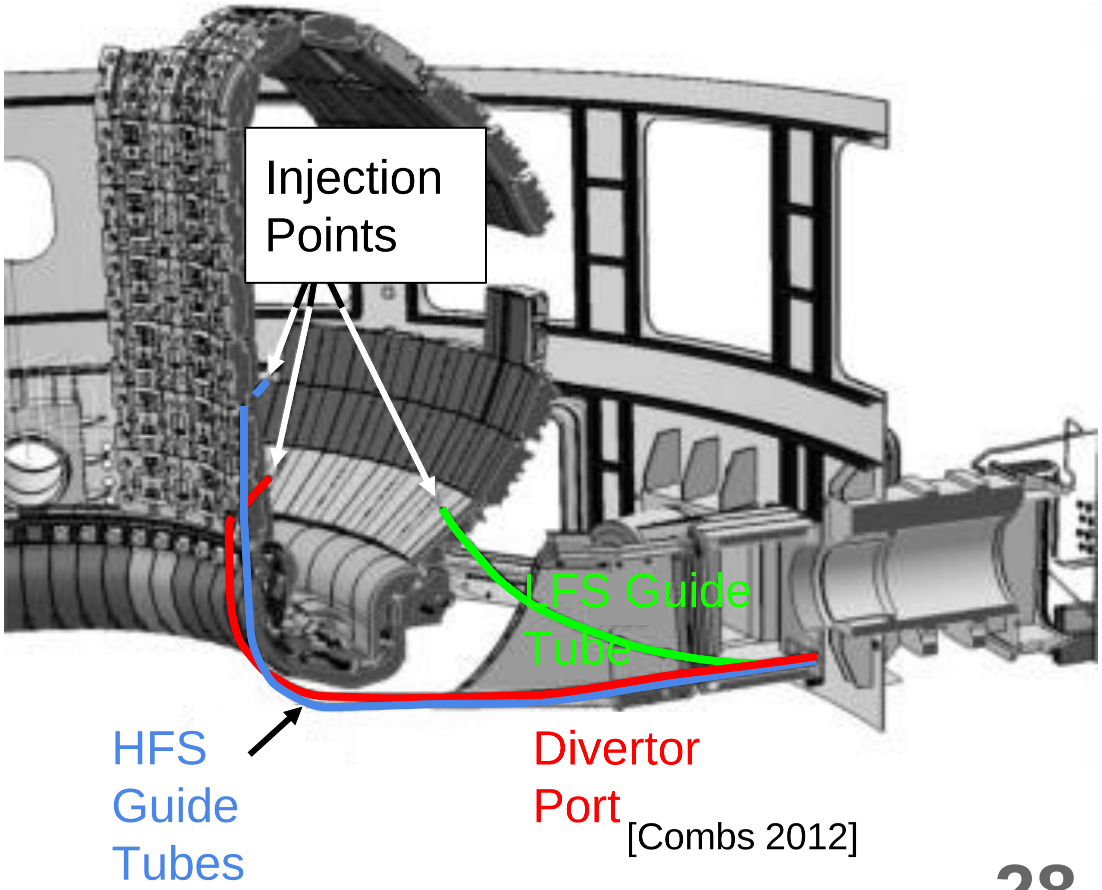
Injector design for JT-60SA and ITER

JT-60SA



[Lang 2019]

ITER



[Combs 2012]

- Midplane or bottom injector
- strong tube bend

5 fueling system dimensioned :

2 under manufacturing :
- JT-60SA (tokamak)
- ITER (tokamak)

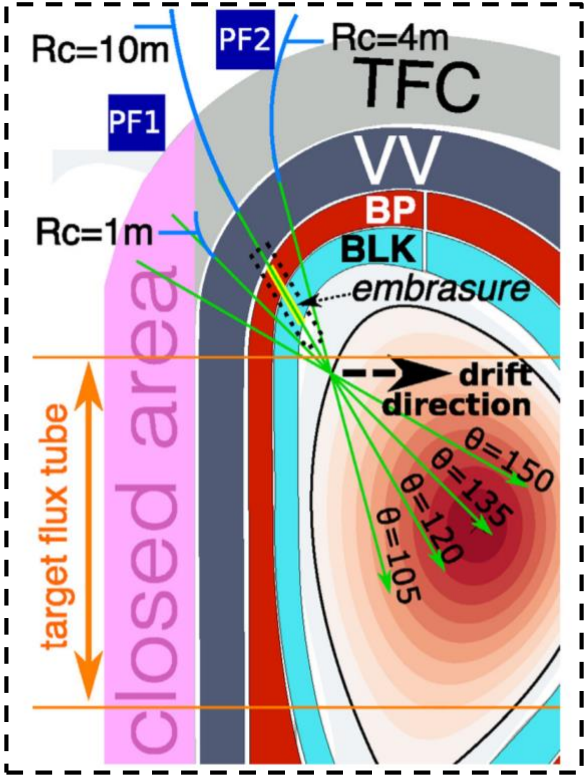
2 as project :
- JA-DEMO (tokamak)
- EU-DEMO (tokamak)

1 preliminary state :
- FFHR (stellarator)

	JT-60SA	ITER	JA-DEMO	EU-DEMO
Injector position	midplane	midplane - bottom		
Injection lines	small R_c	small R_c		
V_p^{Max}	470 m/s	300 m/s		
Injector type	centrifuge	1 stage pneumatic		

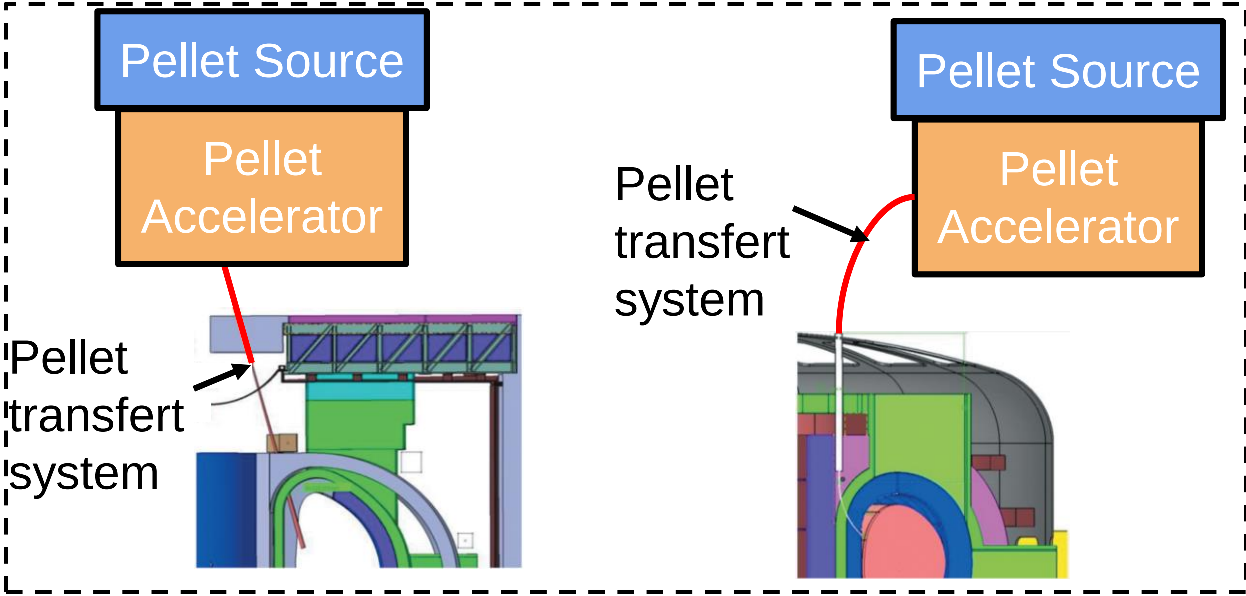
Injector design for JA-DEMO and EU-DEMO

JA-DEMO



[Tokugana 2017]

EU-DEMO



[Poeckl 2021]

Injector design for JA-DEMO and EU-DEMO

5 fueling system dimensioned :

2 under manufacturing :
- JT-60SA (tokamak)
- ITER (tokamak)

2 as project :
- JA-DEMO (tokamak)
- EU-DEMO (tokamak)

1 preliminary state :
- FFHR (stellarator)

	JT-60SA	ITER	JA-DEMO	EU-DEMO	
Injector position	midplane	midplane - bottom	top	top	
Injection lines	small R_c	small R_c	Large R_c	Large R_c	
V_p^{Max}	470 m/s	300 m/s	2000m/s	1700m/s	3000m/s
Injector type	centrifuge	1 stage pneumatic	2 stage pneumatic	centrifuge - 1 stage pneumatic	2 stage pneumatic

5 fueling system dimensioned :

2 under manufacturing :

- JT-60SA (tokamak)
- ITER (tokamak)

2 as project :

- JA-DEMO (tokamak)
- EU-DEMO (tokamak)

1 preliminary state :

- FFHR (stellarator)

Pellet injector in the future devices

	JT-60SA	ITER	JA-DEMO	EU-DEMO		FFHR
Fueling rate	≤ 62mg/s	∈ [20,167]mg/s	50mg/s	∈ [42,58]mg/s		200 mg/s
Pellet Size	∈ [1,5]mg ∈ [2,3]mm	25mg 5mm	17mg 4mm	8mg 3.4mm		**40-60**mg **5.6**mm
V_p^{Max}	470 m/s	300 m/s	2000m/s	1700 m/s	3000 m/s	10 000 m/s

Speed not possible to reach yet

Pellet injector in the future devices

	JT-60SA	ITER	JA-DEMO	EU-DEMO		FFHR
Fueling rate	≤ 62mg/s	∈ [20,125]mg/s	50mg/s	∈ [42,58]mg/s		**600** mg/s
Pellet Size	∈ [1,5]mg ∈ [2,3]mm	25mg 5mm	17mg 4mm	8mg 3.4mm		40-60mg 5.6mm
V_p^{Max}	470 m/s	300 m/s	2000m/s	1700 m/s	3000 m/s	1200 m/s

Not possible to increase pellet size

⇒ unacceptable jumps in fusion power & heat loads of the divertor

Summary

- Understand **Ablation and Homogenization physic** let us understand differences for tokamak/stellarator/RFP

- Fuelling using pellets allows **high performance discharges**

Tokamak	Stellarator
• $> n_{gw}$ without ELMs	• $\tau_E \nearrow$ • Peak density profil

- **Pellet injection line** to be considered from **very early stage** of the design of future devices.
  - → allows better fuelling efficiency
  - → reduced fuelled circulation