Nov. 16th 2015

Faculty of Nuclear Sciences and Physical Engineering, CTU Prague

Interaction between neutral beam fast particles and plasma in fusion experiments

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FuseNet PhD Event 2015

Outline

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Ricerca Formazione Innovazione

- Introduction
- NBI physics
- NBI history and future
- NBI modelling
- NBI-plasma interaction at LHD

Introduction

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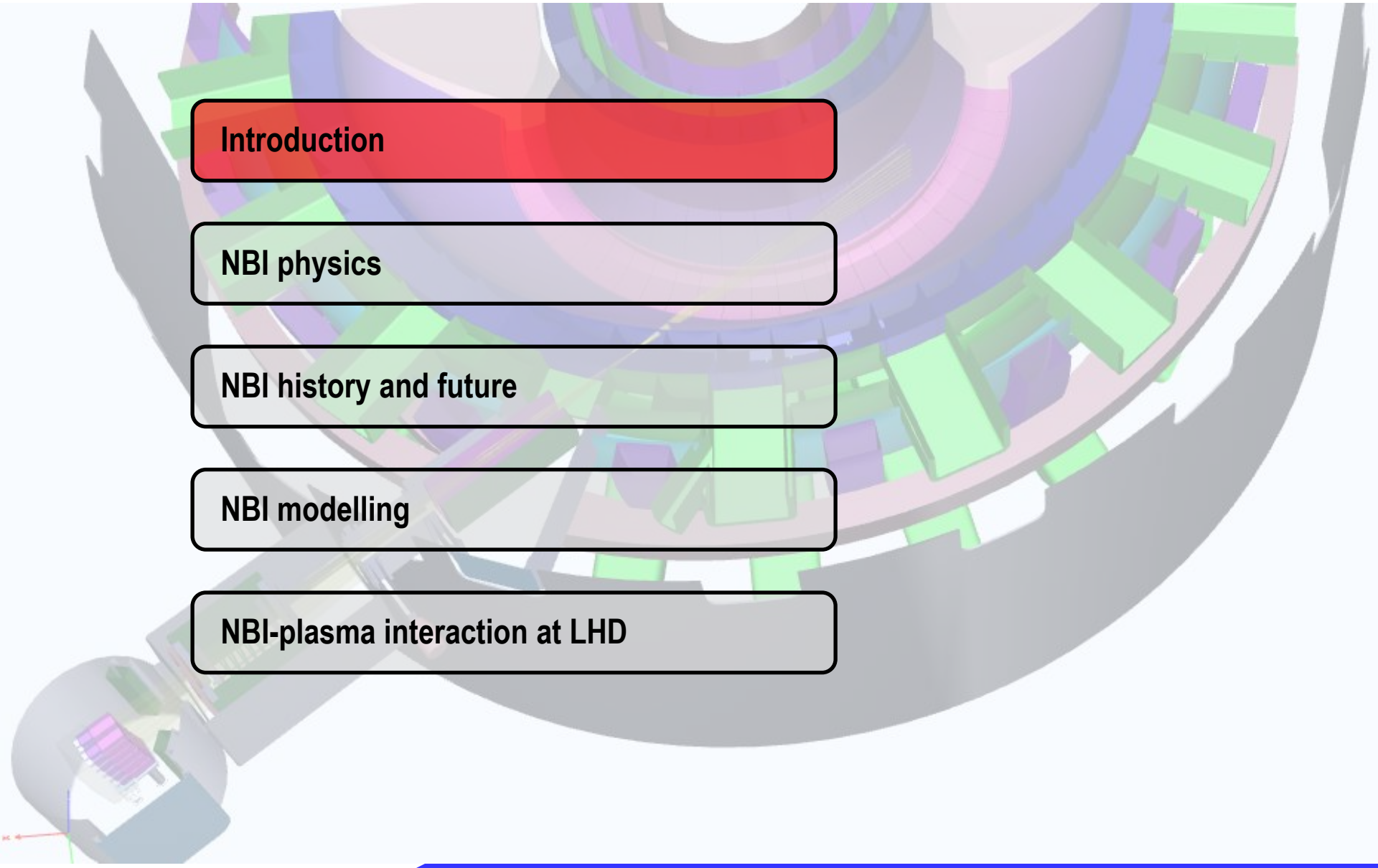

- **Introduction**
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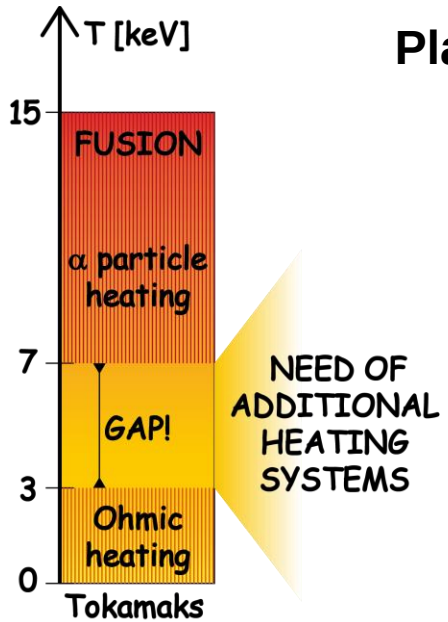
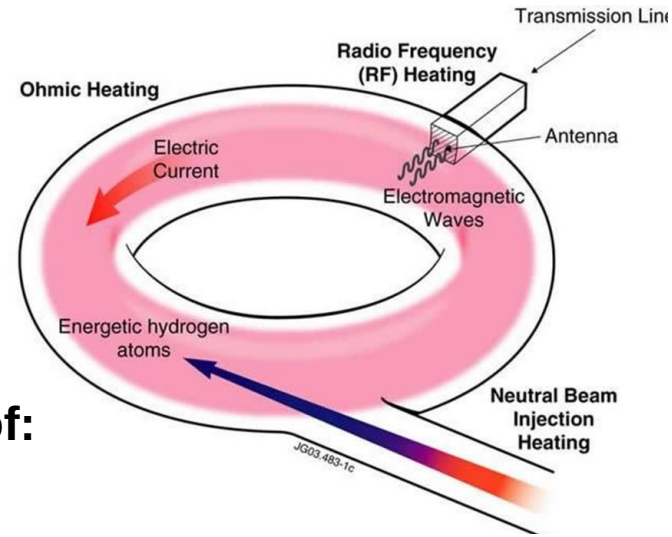
- **NBI-plasma interaction at LHD**

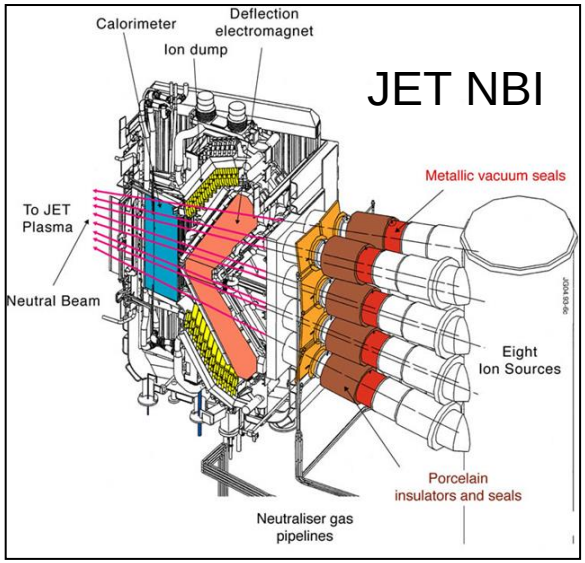
Neutral Beam Injection (NBI)



Plasma heating by Neutral Beam Injection (NBI)

In Tokamak reactors external additional heating is required to approach ignition. One of the most utilized systems is **Neutral Beam Injection** (NBI): injection of energetic neutral particles ($E_{k,beam} >> E_{k,plasma}$) which enter the plasma and are ionized by the background plasma becoming "fast ions".





NBI can be also a source of:

- Current
- Particles
- Momentum torque
- Suprathermal ion population
- Fusion reactions

NBI-plasma interaction physics

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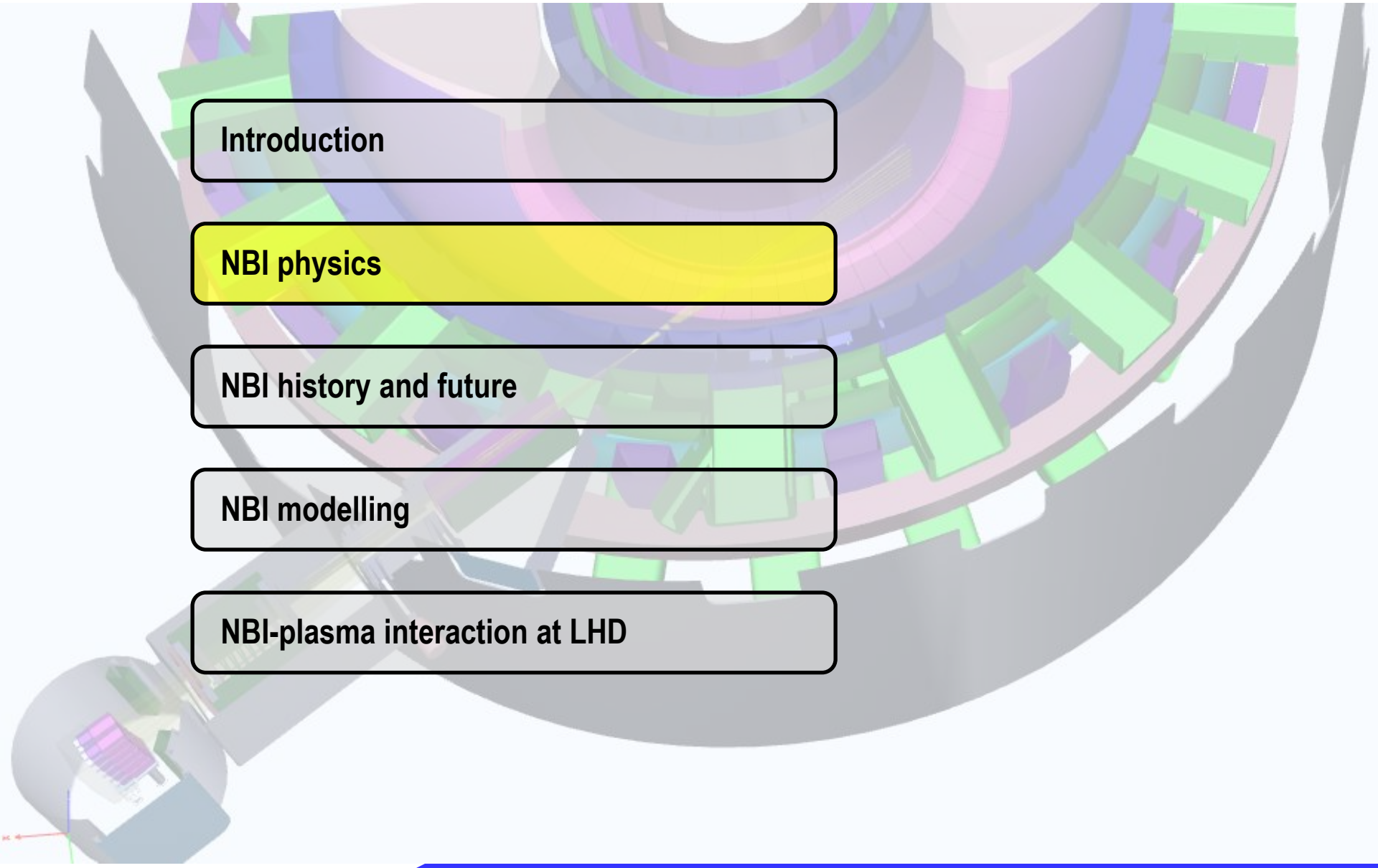

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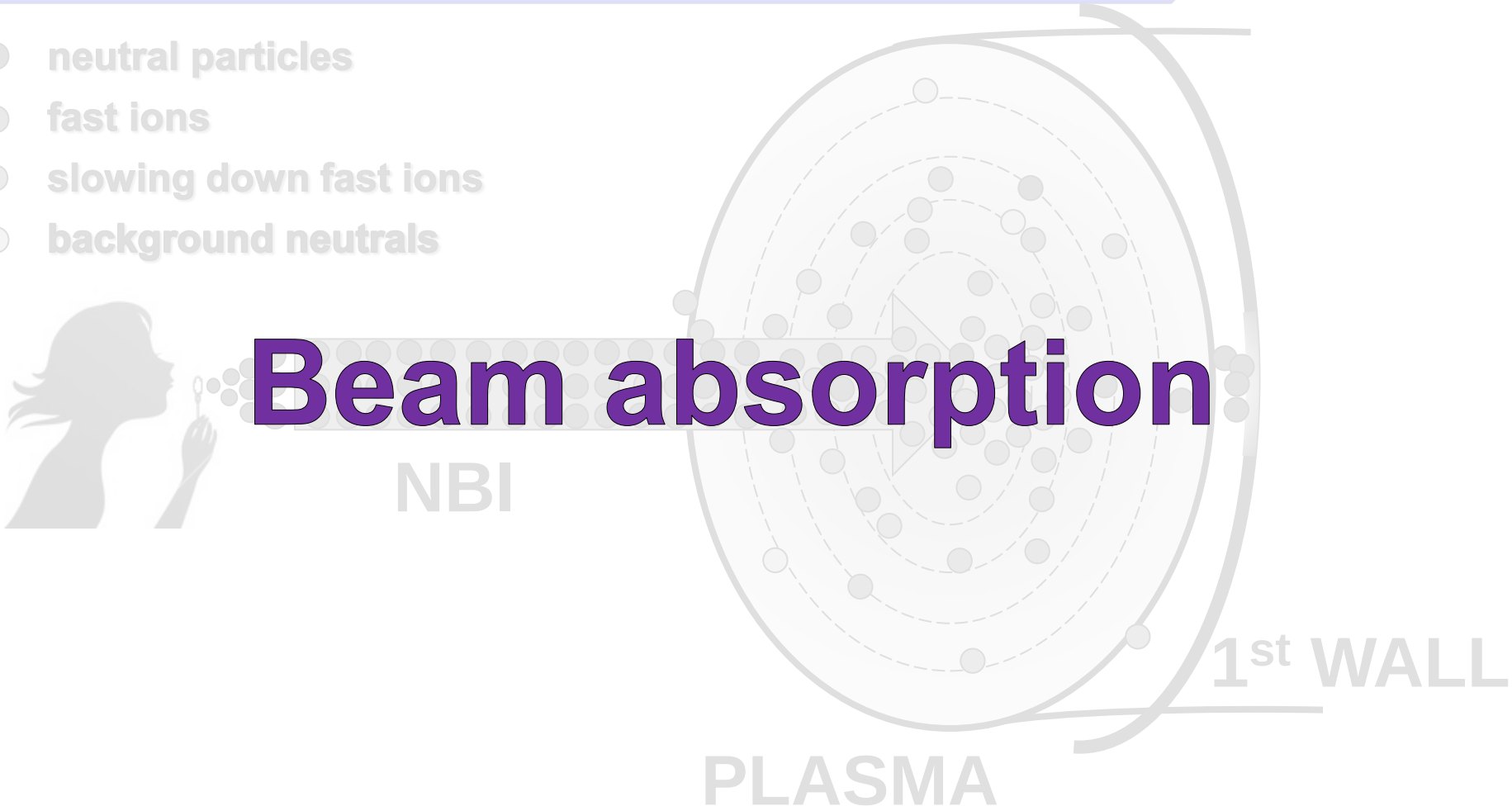
NBI-plasma interaction physics

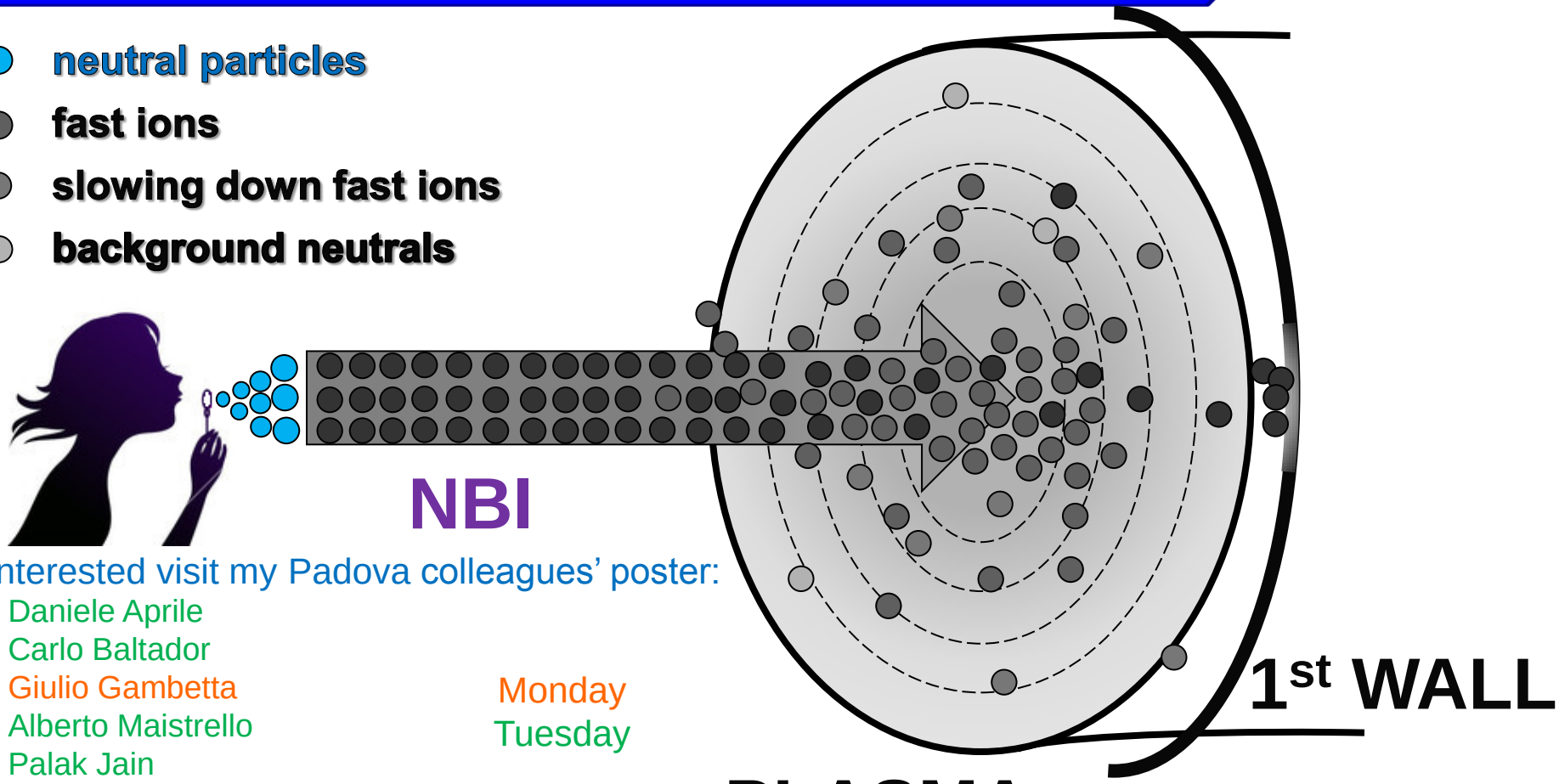
- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



Beam absorption

Neutral beam generation

- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



If interested visit my Padova colleagues' poster:

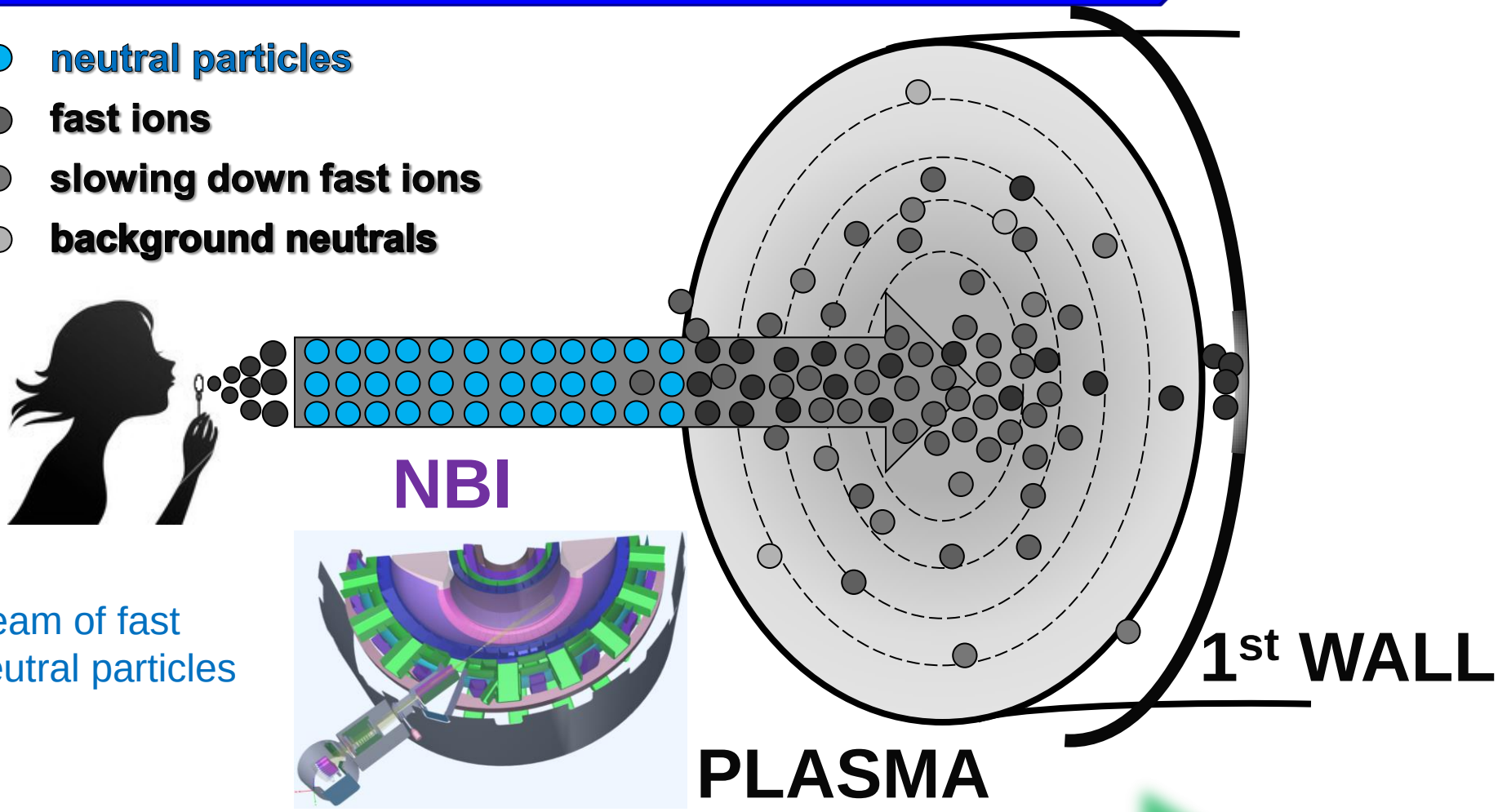
- Daniele Aprile
- Carlo Baltador
- Giulio Gambetta
- Alberto Maistrello
- Palak Jain
- Antonio Pimazzoni
- Matteo Zaupa

Monday
Tuesday

neutral beam generation | neutral particles | ionization | fast ion slowing down

Beam of fast neutral particles

- neutral particles
- fast ions
- slowing down fast ions
- background neutrals

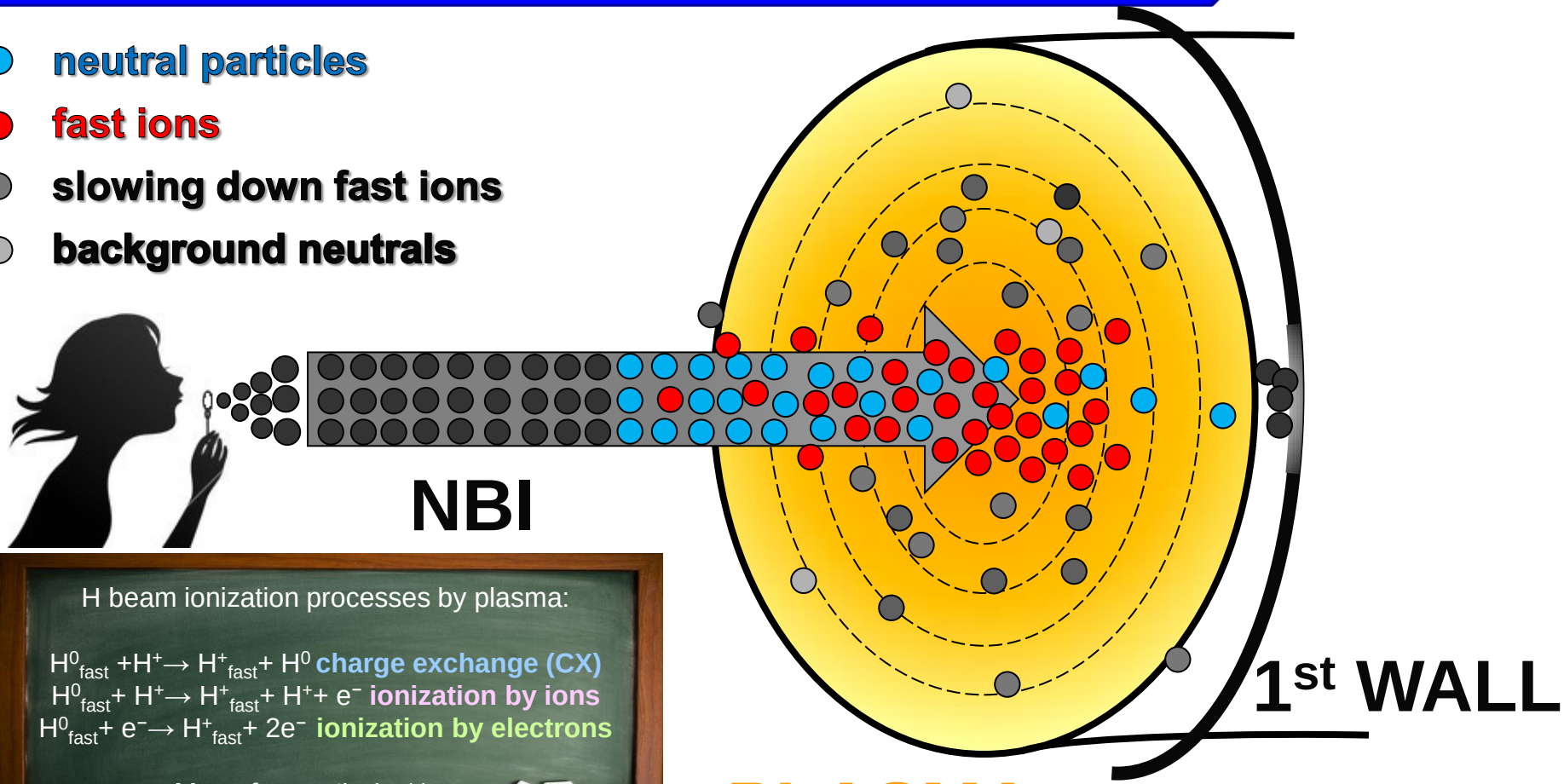


Beam of fast neutral particles

neutral beam generation | neutral particles | ionization | fast ion slowing down

Neutral beam ionization

- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



H beam ionization processes by plasma:

$H^0_{fast} + H^+ \rightarrow H^+_{fast} + H^0$ charge exchange (CX)

$H^0_{fast} + H^+ \rightarrow H^+_{fast} + H^+ + e^-$ ionization by ions

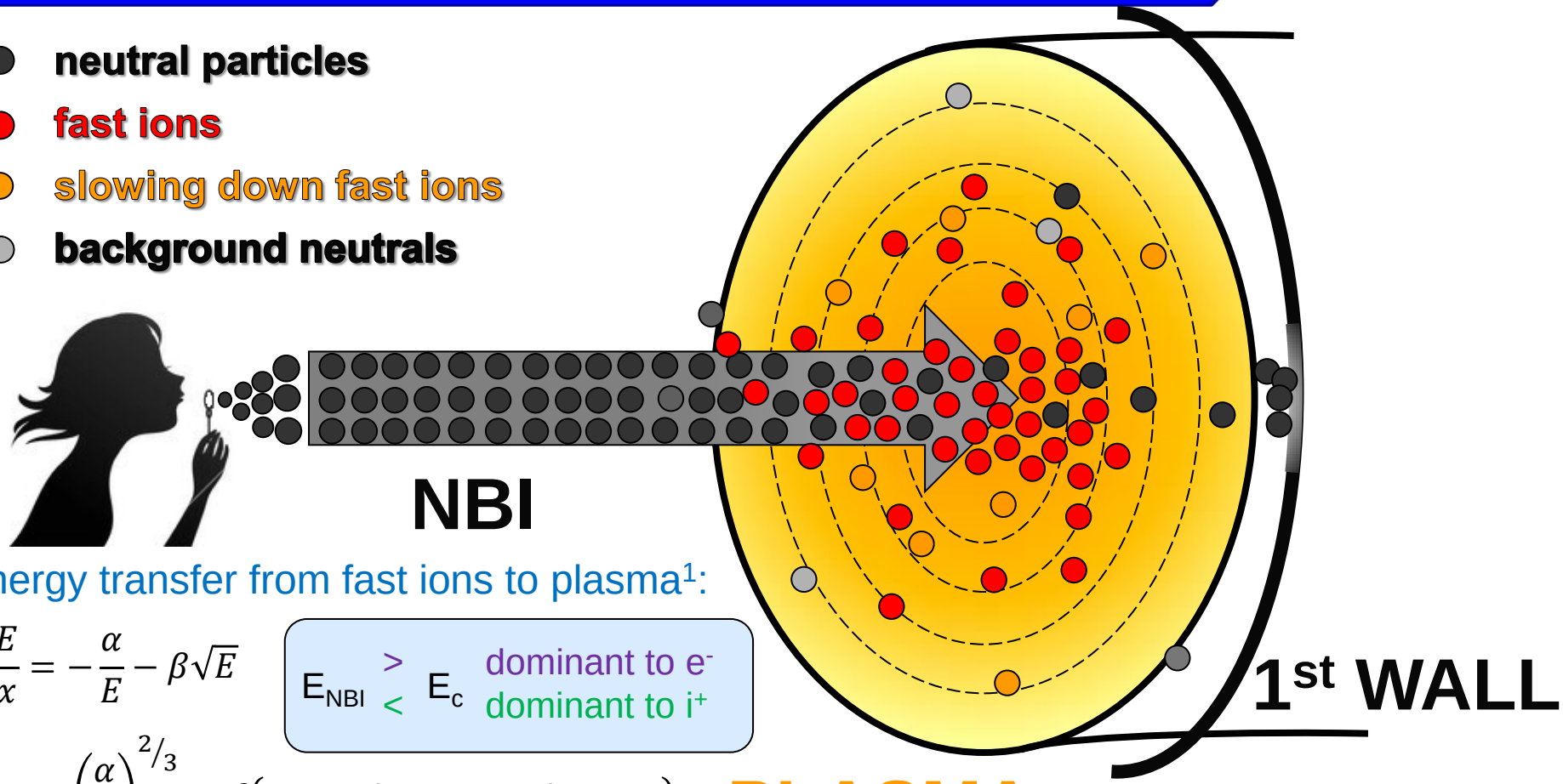
$H^0_{fast} + e^- \rightarrow H^+_{fast} + 2e^-$ ionization by electrons

Mean free path: $\lambda = 1/n\sigma_{tot}$

neutral beam generation | neutral particles | ionization | fast ion slowing down

Fast ion slowing down

- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



Energy transfer from fast ions to plasma[1]:

$$\frac{dE}{dx} = -\frac{\alpha}{E} - \beta\sqrt{E}$$

$E_{NBI} > E_c$ dominant to e^-

$E_{NBI} < E_c$ dominant to i^+

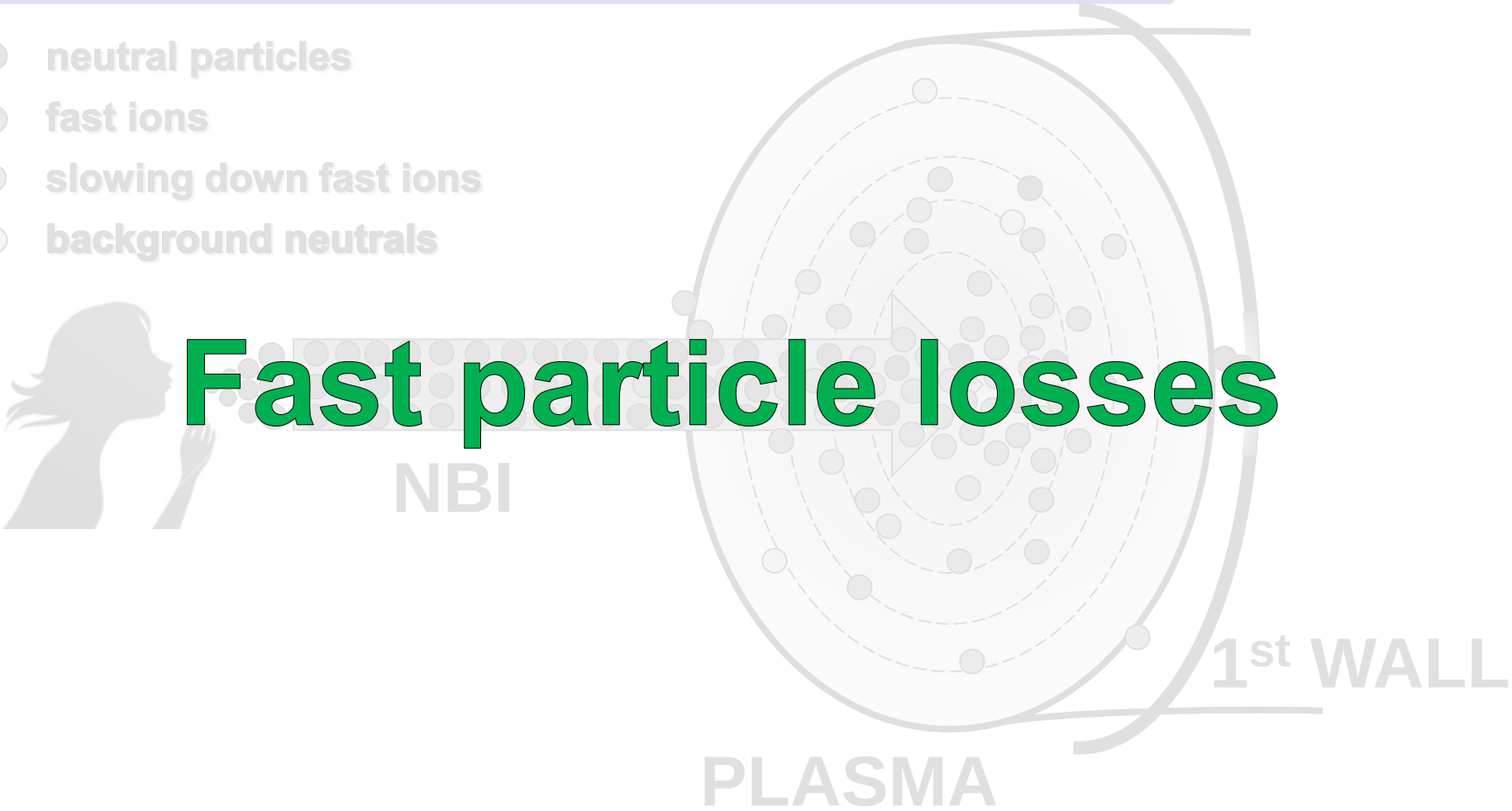
$$E_c = \left(\frac{\alpha}{\beta}\right)^{2/3} = f\left(T_e, n_e, A_{NBI}, Z_{NBI}, A_j, Z_j, n_j\right)$$

neutral beam generation | neutral particles | ionization | fast ion slowing down

[1]T. Stix, Plasma Phys. 14 (1972) 367

NBI-plasma interaction physics

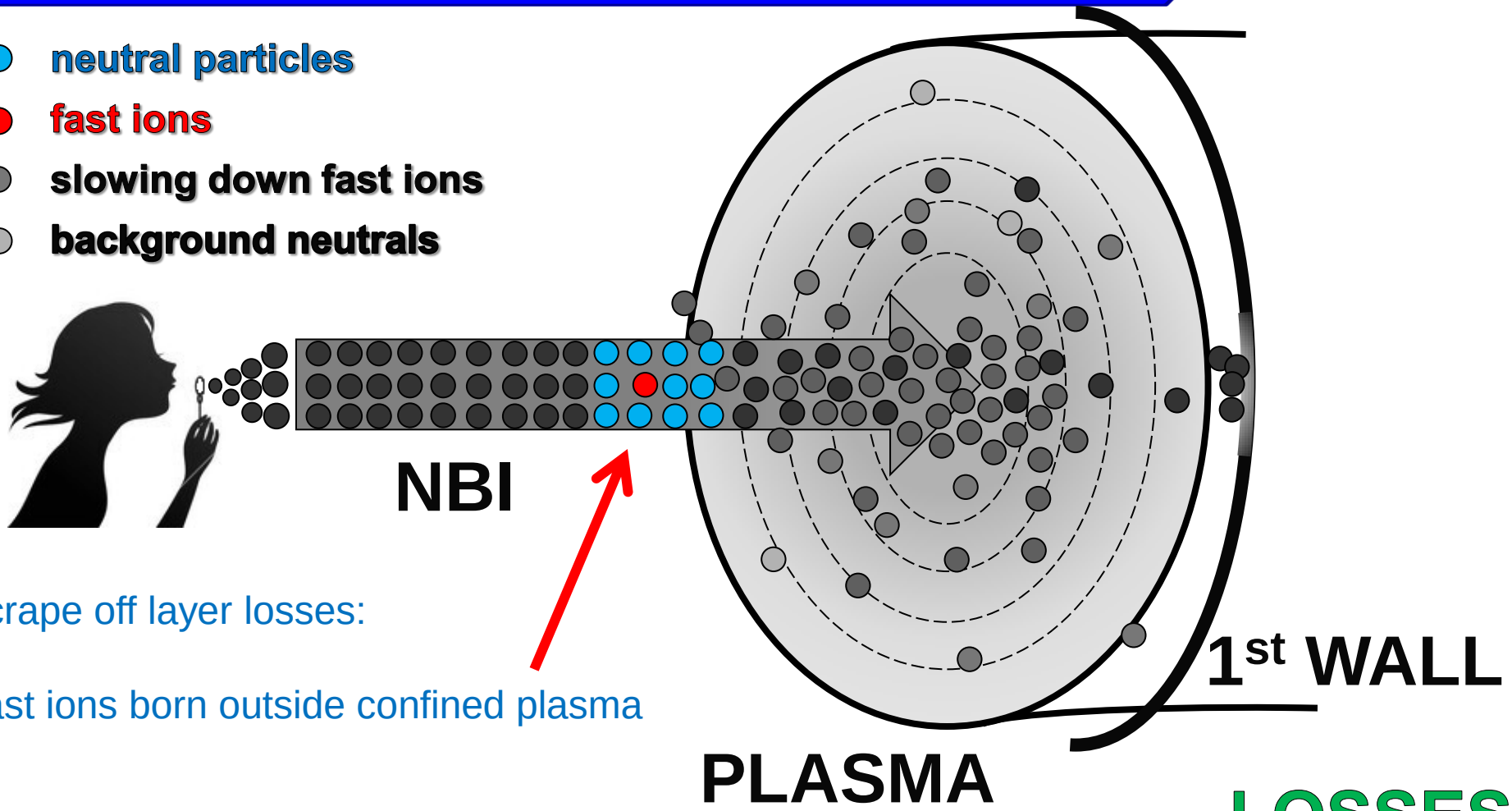
- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



Fast particle losses

Scrape off layer losses

- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



Scrape off layer losses:

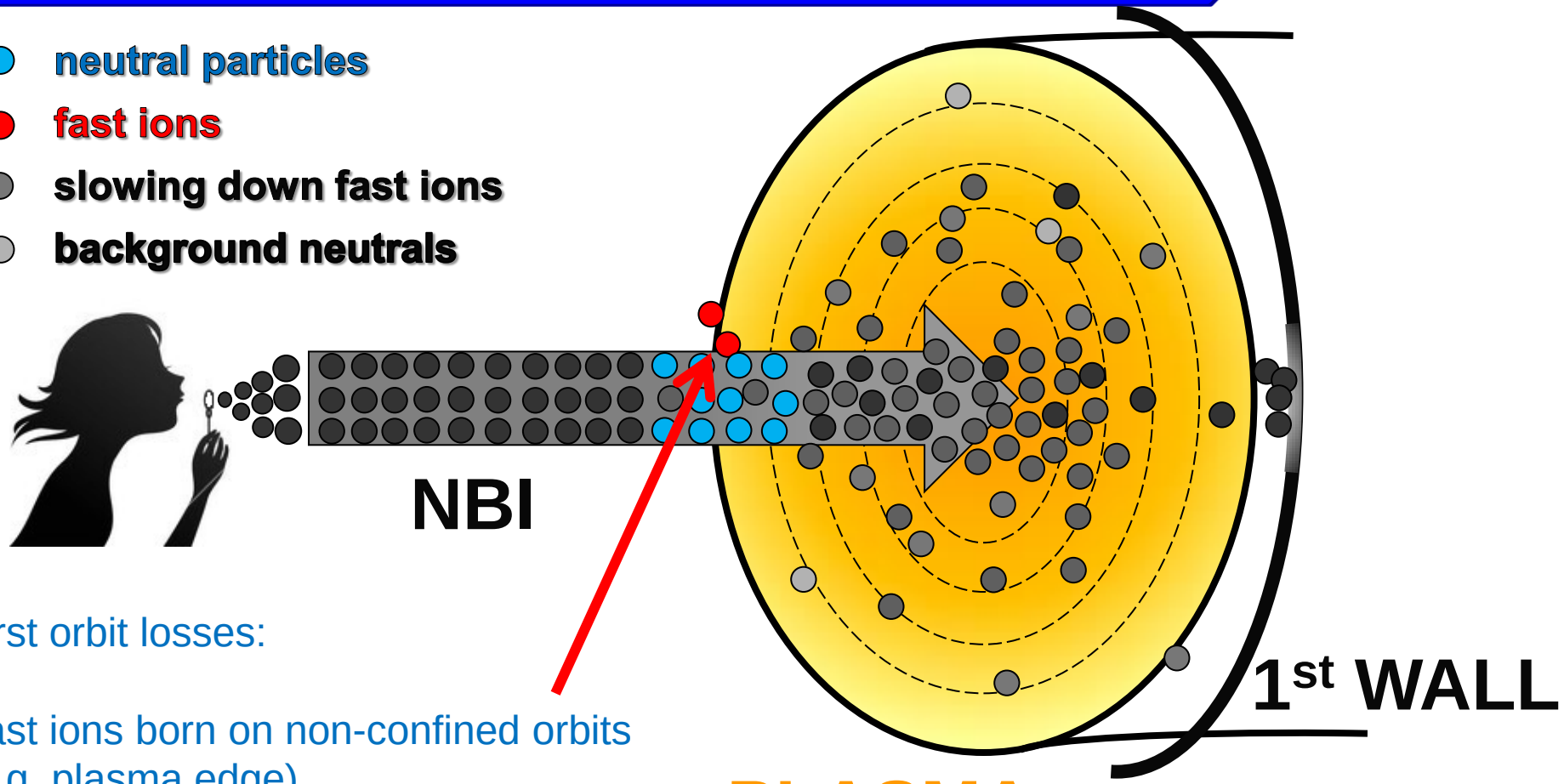
Fast ions born outside confined plasma

LOSSES

Scrape off layer	First orbit	Charge-exchange	Orbit	Shine-through

First orbit losses

- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



First orbit losses:

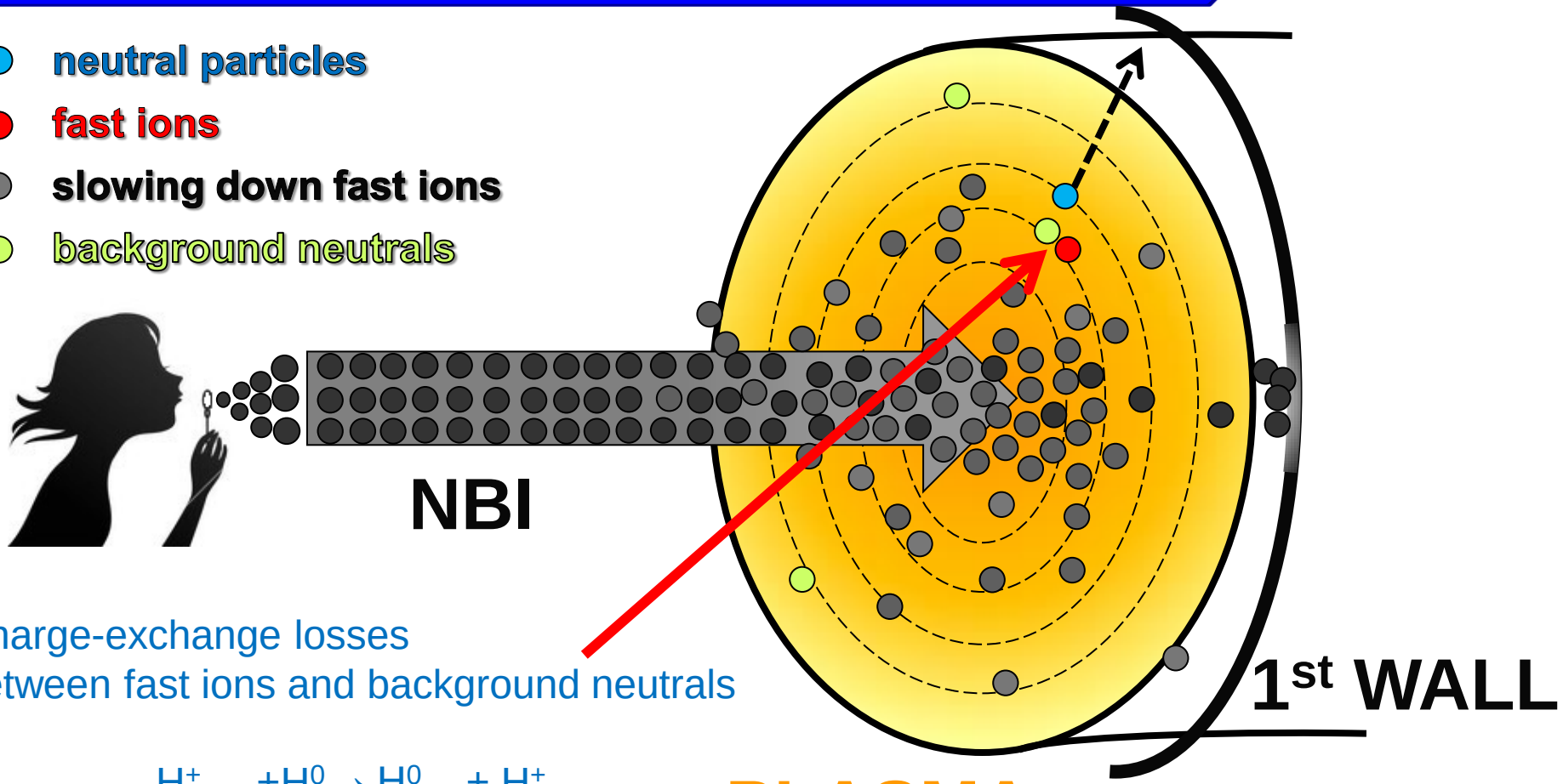
Fast ions born on non-confined orbits (e.g. plasma edge)

LOSSES

Scrape off layer	First orbit	Charge-exchange	Orbit	Shine-through

CX losses

- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



Charge-exchange losses
between fast ions and background neutrals

$H^+_{fast} + H^0 \rightarrow H^0_{fast} + H^+$

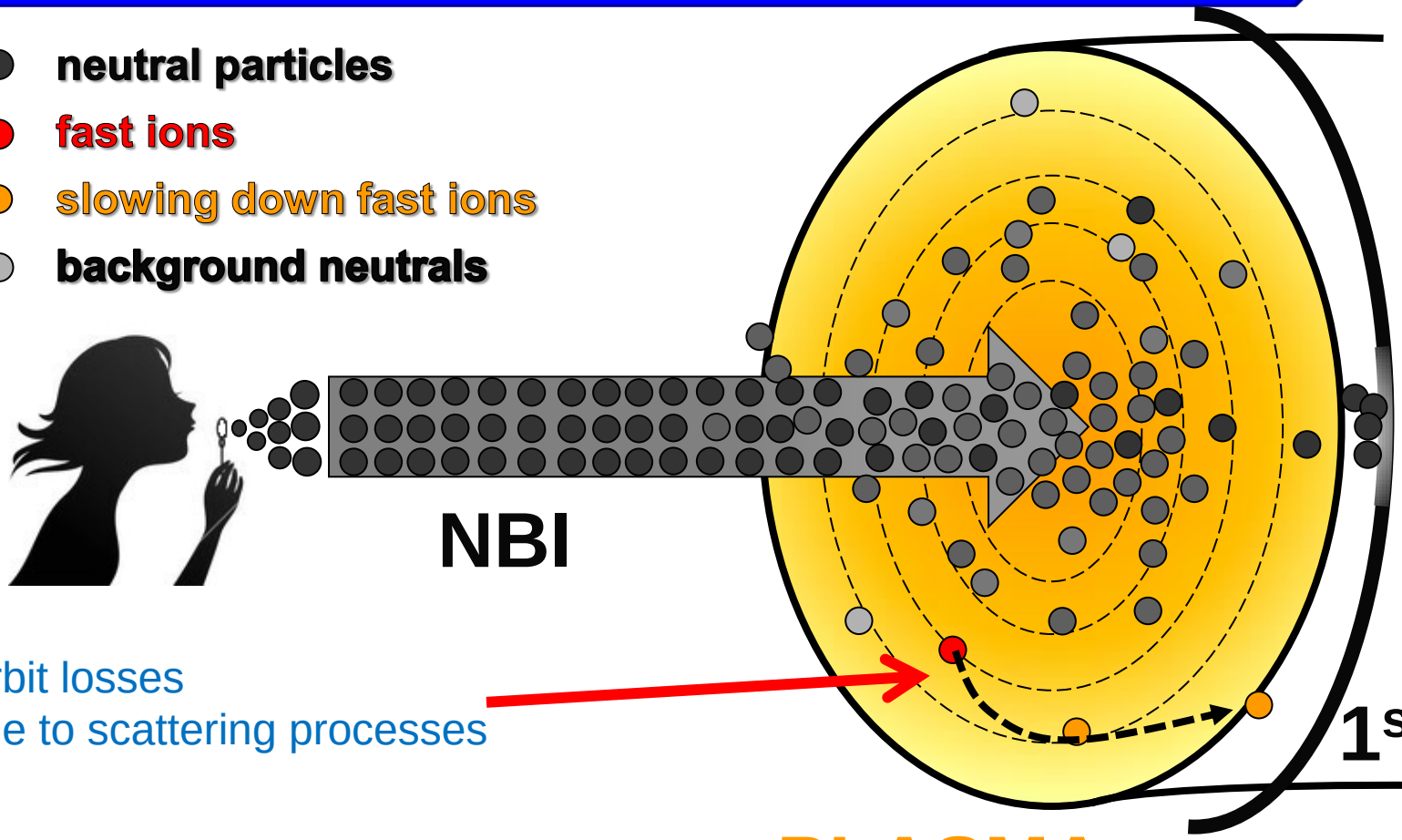
PLASMA

LOSSES

Scrape off layer	First orbit	Charge-exchange	Orbit	Shine-through

Orbit losses

- neutral particles
- fast ions
- slowing down fast ions
- background neutrals



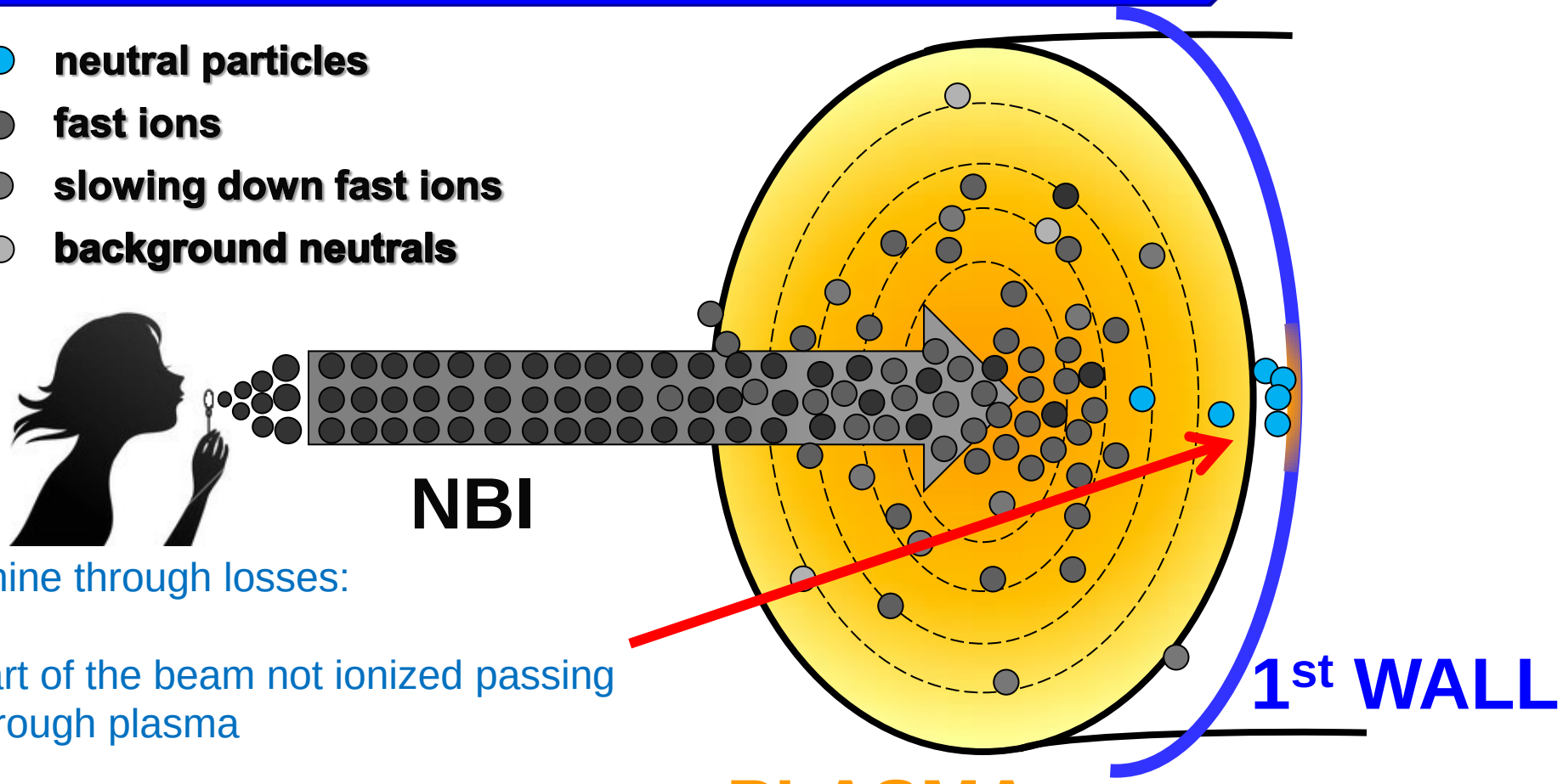
Orbit losses
due to scattering processes

LOSSES

Scrape off layer	First orbit	Charge-exchange	Orbit	Shine-through

Shine-through losses

- **neutral particles**
- **fast ions**
- **slowing down fast ions**
- **background neutrals**



Shine through losses:

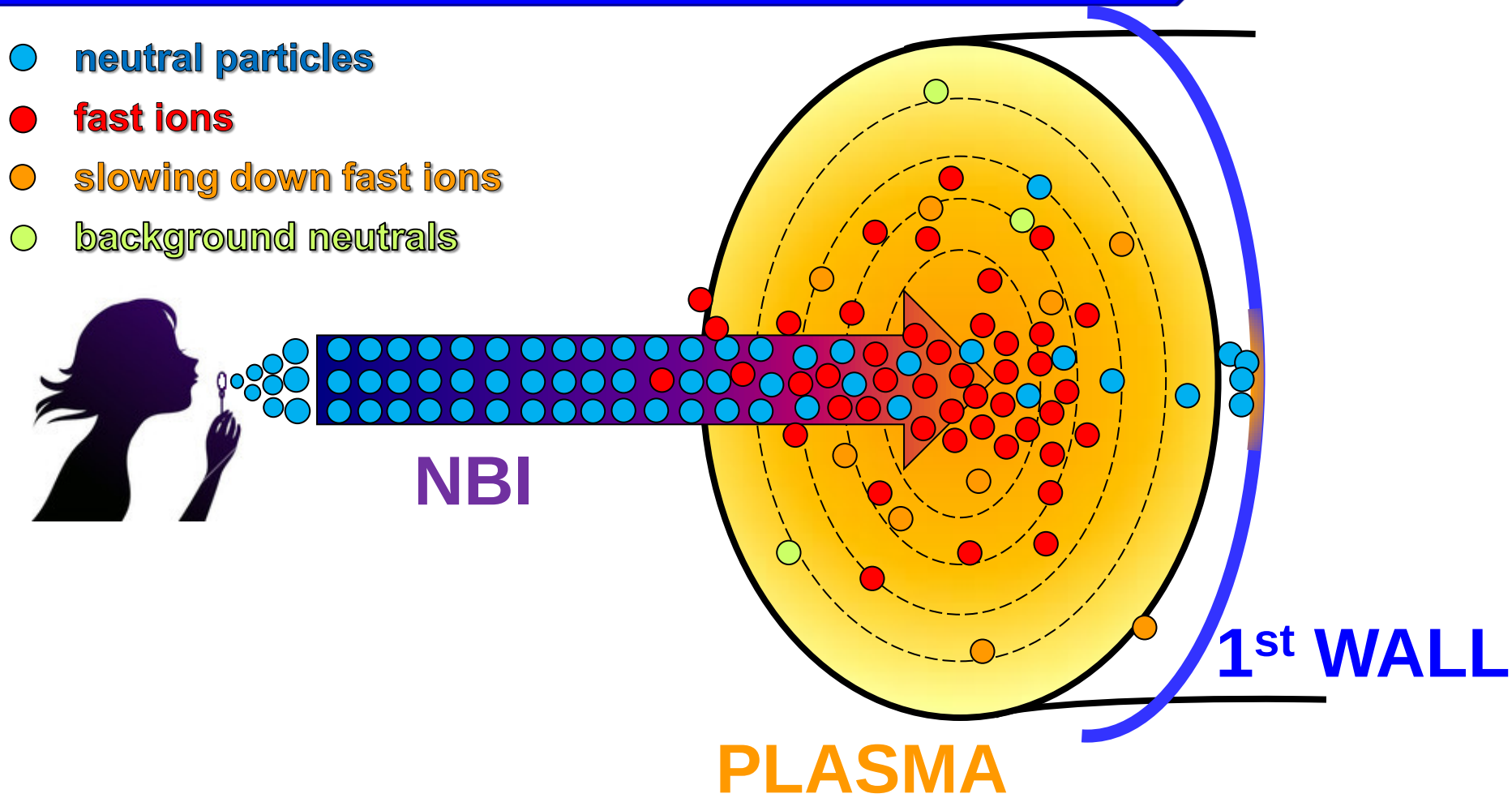
part of the beam not ionized passing through plasma

(harmful for 1st wall heat load)

LOSSES

Scrape off layer	First orbit	Charge-exchange	Orbit	Shine-through

NBI-plasma interaction physics



The complete picture!

NBI history and future

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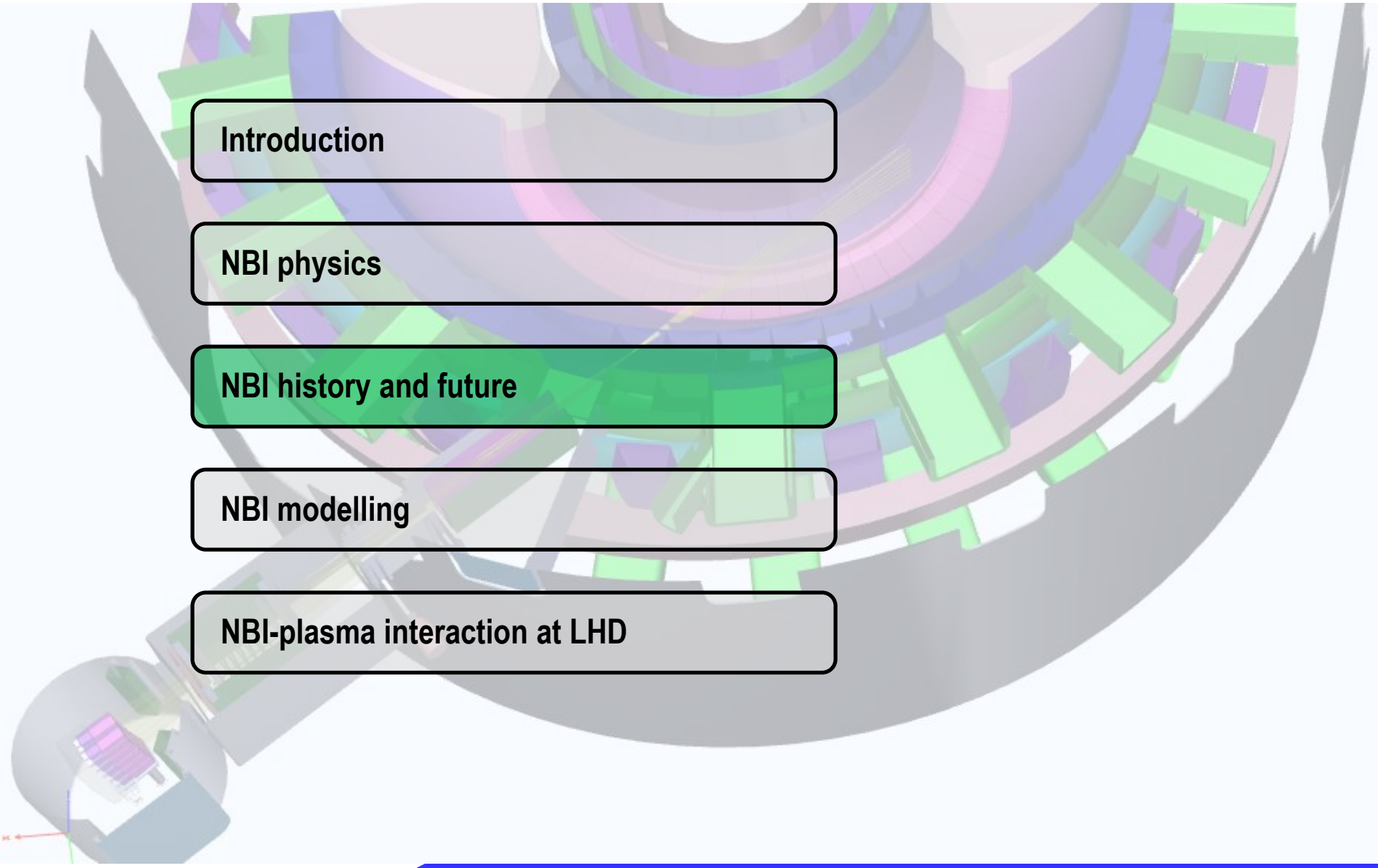

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NBI history

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timeline

Early 1970s

First proof of NBI heating principle
H. Eubank et al., IAEA (1978)
H. Eubank et al., PRL **43** (1979) 4

Neutral-Beam–Heating Results from the Princeton Large Torus

H. Eubank, R. Goldston, V. Arunasalam, M. Bitter, K. Bol, D. Boyd,[a] N. Bretz, J.-P. Bussac,[b] S. Cohen, P. Colestock, S. Davis, D. Dimock, H. Dylla, P. Efthimion, L. Grisham, R. Hawryluk, K. Hill, E. Hinnov, J. Hosea, H. Hsuan, D. Johnson, G. Martin, S. Medley, E. Meservey, N. Sauthoff, G. Schilling, J. Schivell, G. Schmidt, F. Stauffer,[d] L. Stewart,[c] W. Stodiek, R. Stooksberry,[d] J. Strachan, S. Suckewer, H. Takahashi, G. Tait,[d] M. Ulrickson, S. von Goeler, and M. Yamada
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544
and
C. Tsai, W. Stirling, W. Dagenhart, W. Gardner, M. Menon, and H. Haselton
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 1 March 1979)

1982

Discovery of high confinement mode with NBI
Wagner et al., PRL **49** (1982) 1408

Regime of Improved Confinement and High Beta in Neutral-Beam–Heated Divertor Discharges of the ASDEX Tokamak

F. Wagner, G. Becker, K. Behringer, D. Campbell, A. Eberhagen, W. Engelhardt, G. Fussmann, O. Gehre, J. Gernhardt, G. v. Gierke, G. Haas, M. Huang,[a] F. Karger, M. Keilhacker, O. Klüber, M. Kornherr, K. Lackner, G. Lisitano, G. G. Lister, H. M. Mayer, D. Meisel, E. R. Müller, H. Murmann, H. Niedermeyer, W. Poschenrieder, H. Rapp, H. Röhr, F. Schneider, G. Siller, E. Speth, A. Stäbler, K. H. Steuer, G. Venus, O. Vollmer, and Z. Yü[a]
Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-8046 Garching, München, Germany
(Received 6 August 1982; revised manuscript received 1 October 1982)

1994 - 1998

D-T experiments at TFTR and JET with dominant NBI heating and high P_{fus}
Hawryluk et al. PRL **72** (1994) 3530
Strachan et al. PRL **72** (1994) 3526
Keilhacker et al., Nucl. Fusion **39** (1999) 209
Hawryluk et al., Rev. Mod. Phys. **70** (1998) 553

VOLUME 72, NUMBER 22 PHYSICAL REVIEW LETTERS 30 MAY 1994

Fusion Power Production from TFTR Plasmas Fueled with Deuterium and Tritium

J. D. Strachan,[1] H. Adler,[1] P. Alling,[1] C. Ancher,[1] H. Anderson,[1] J. L. Anderson,[2] D. Ashcroft,[1] Cris W. Barnes,[2] G. Barnes,[1] S. Batha,[3] M. G. Bell,[1] R. Bell,[1] M. Bitter,[1] W. Blanchard,[1] N. L. Bretz,[1] R. Budny,[1] C. E. Bush,[4] R. Camp,[1] M. Caorlin,[1] S. Cauffman,[1] Z. Chang,[5] C. Z. Cheng,[1] J. Collins,[1] G.

2010s

ITER experiment construction, including the highest energy NBI (1MeV) ever built
V. Antoni et al., Rev. Sci. Instrum. **85** (2014)

REVIEW OF SCIENTIFIC INSTRUMENTS 85, 02B128 (2014)

Physics design of the injector source for ITER neutral beam injector (invited)[a)]

V. Antoni,[1] P. Agostinetti,[1] D. Aprile,[1] M. Cavenago,[2] G. Chitarin,[1] N. Fonnesu,[1] N. Marconato,[1] N. Pilan,[1] E. Sartori,[1] G. Serianni,[1,b)] and P. Veltri[1]
[1]*Consorzio RFX, Associazione EURATOM-ENEA sulla fusione, c.so Stati Uniti 4, 35127 Padova, Italy*
[2]*INFN-LNL, viale dell'Università n. 2, 35020 Legnaro, Italy*

(Presented 10 September 2013; received 21 September 2013; accepted 2 December 2013; published online 7 January 2014)

future

NBI is planned to be used on EU DEMO demonstrative reactor
T. Franke et al., "On the present status of the EU DEMO H&CD", IEEE Symposium on Fusion Engineering (SOFE 2015), Austin, TX

NBI…towards future

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		Present day	ITER/DEMO
NBI technology	Energy	Low-middle (40-200 up to 500 keV - JT60SA)	High 800-1000 keV
	Power	Tens MW	Tens MW
NBI physics	Heating source	✓	✓
	Driven current source	✓	✓
	Particle source	✓	Negligible
	Torque source	✓	Negligible
	Fusion reactions (beam-plasma) source	✓	Relatively low

NBI modelling

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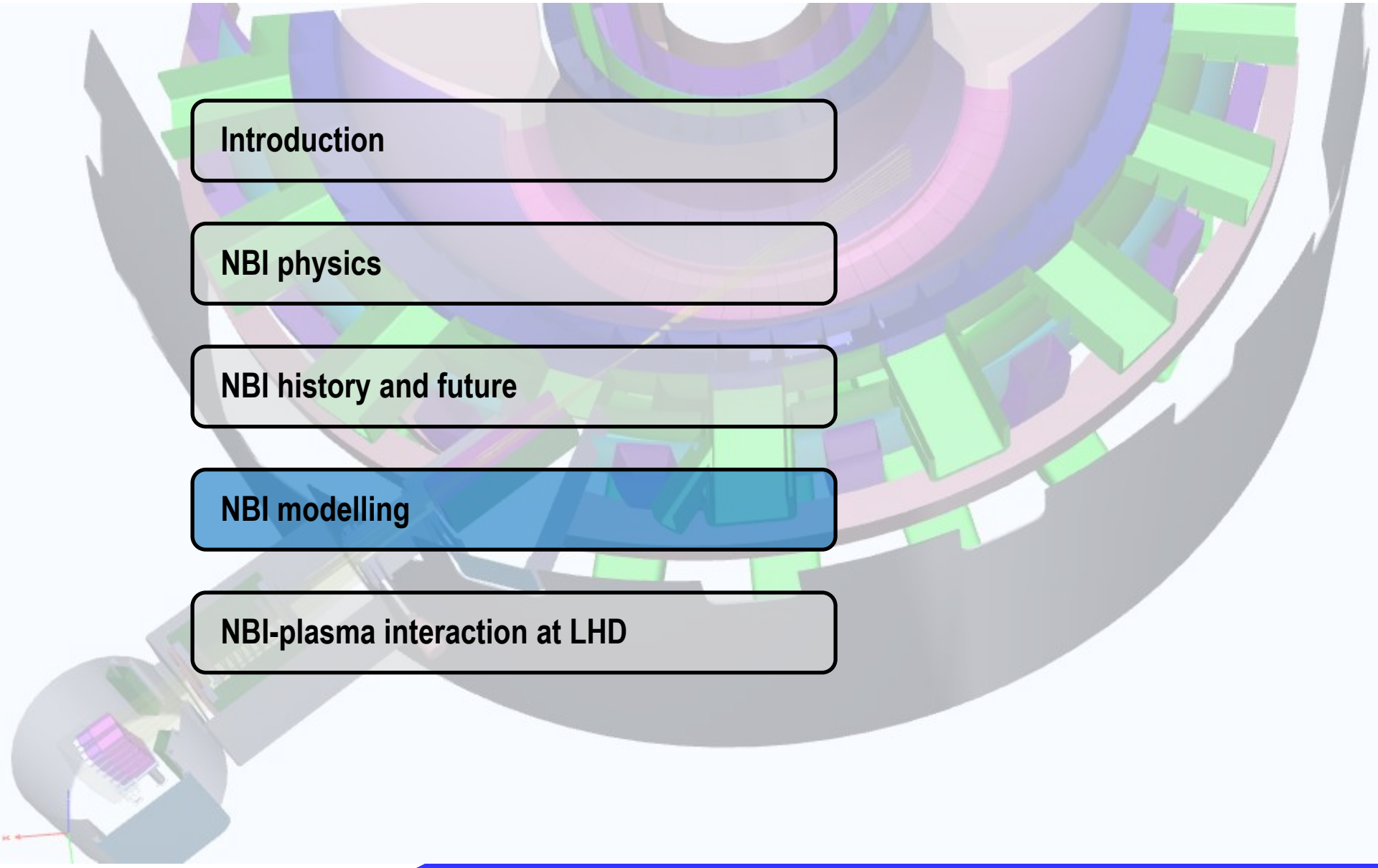

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From low to high NBI modelling resolution

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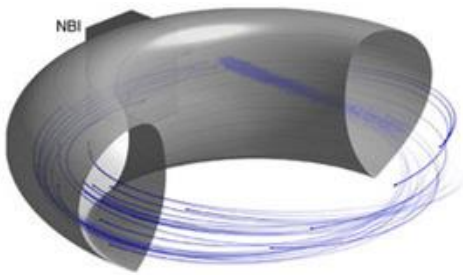
Numerical codes calculate NBI ionization and fast ions slowing down

Output:

- Fast ion birth profile
- Power transferred to plasma (ions or electrons)
- NBI losses (e.g. shine thorugh)
- Driven current
- Momentum transferred to plasma
- …



NBI models

fast codes using analytical solutions of fast ion Fokker-Planck equation, well suitable for sensitivity studies.
Simplified approach

vs

Orbit-following Monte Carlo codes solving kinetic equation for fast ions, which can take into account fast ions orbit effects.
Long simulation time, but detailed

NBI simulations

Stand alone: NBI acting on “frozen” plasma
Integrated: NBI interacting with evolving plasma, coupled to e.g. transport codes

NBI-plasma interaction at LHD

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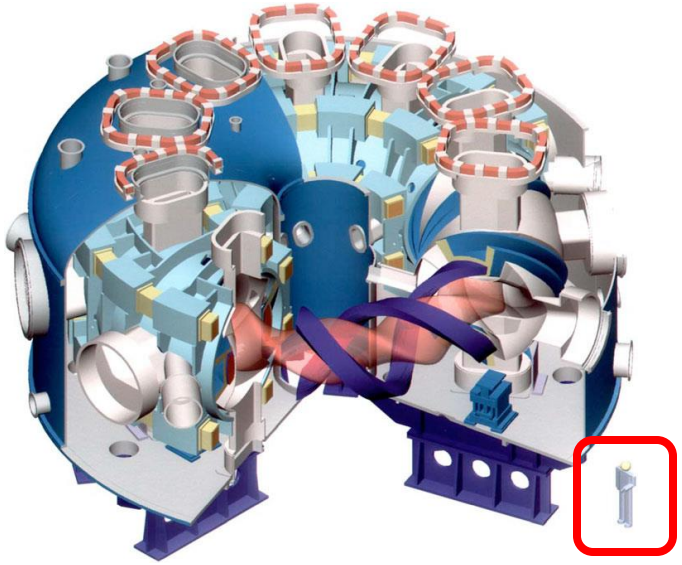
LHD experiment

LHD[1] is the world's largest heliotron type device in operation.
Thanks to superconducting coils it is able to study current-free plasmas.

NIFS, Toki, Japan



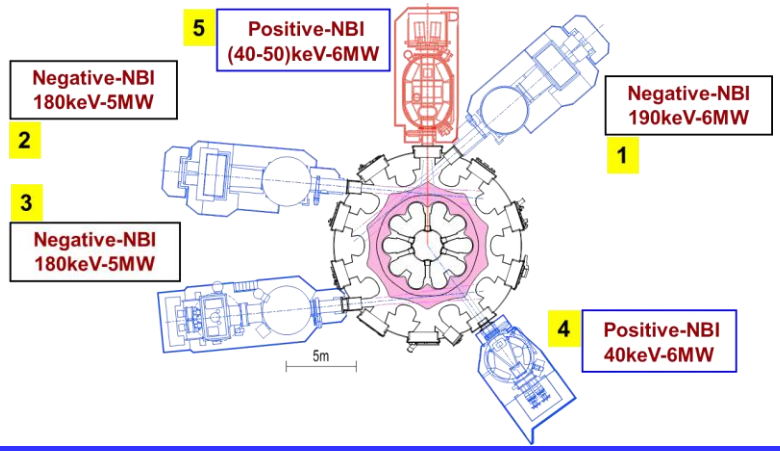
PERSON

LHD parameters	
Major radius	3.9 m
Minor plasma radius	0.5 – 0.65 m
Magnetic field	3 T at R=3.9 m
Plasma volume	30 m^3
ECRH	10 MW
ICRH	3 MW
NBI	15-23 MW

NBI system at LHD

5 NBI systems:

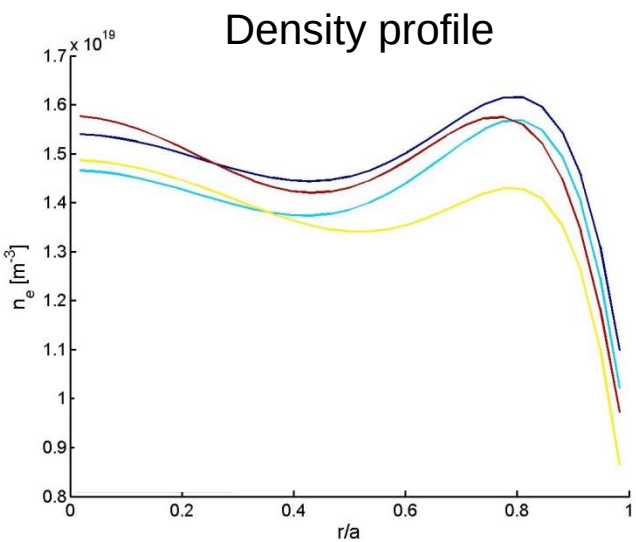
- 2 perpendicular NBIs (40-50 keV, up to 12MW)
- 3 tangential (co- and counter-current) NBIs (180-190 keV, up to 16MW)

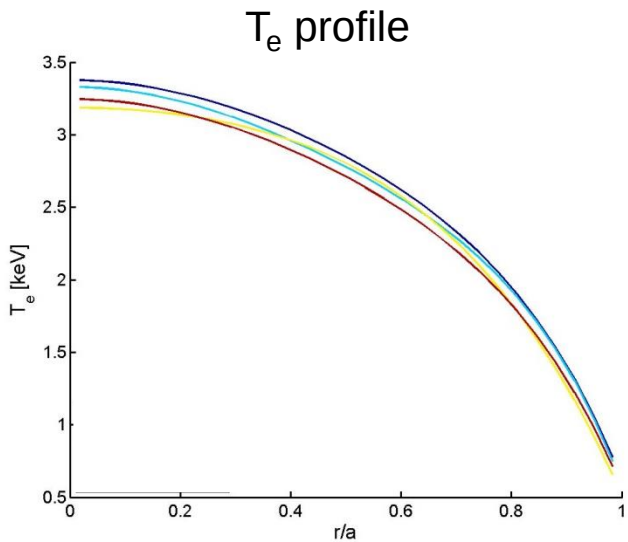


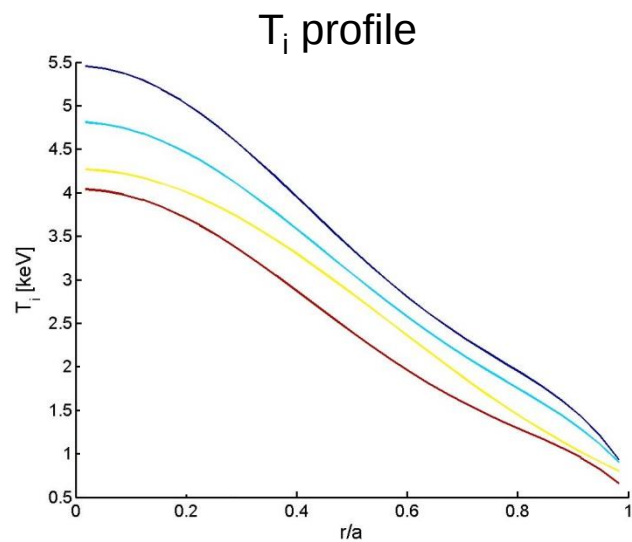
[1]O. Motojima et al, Nucl. Fusion 40 (2000) 599

Similarity H/He experiments at LHD

- 4 similar LHD shots varying the plasma composition from H to He majority
- Dominant NBI heating
- Similar n_e and T_e, while higher T_i with He majority







SHOT	H/(H+He)
128670	0,34
128665	0,48
128708	0,73
128717	0,78

→ He majority

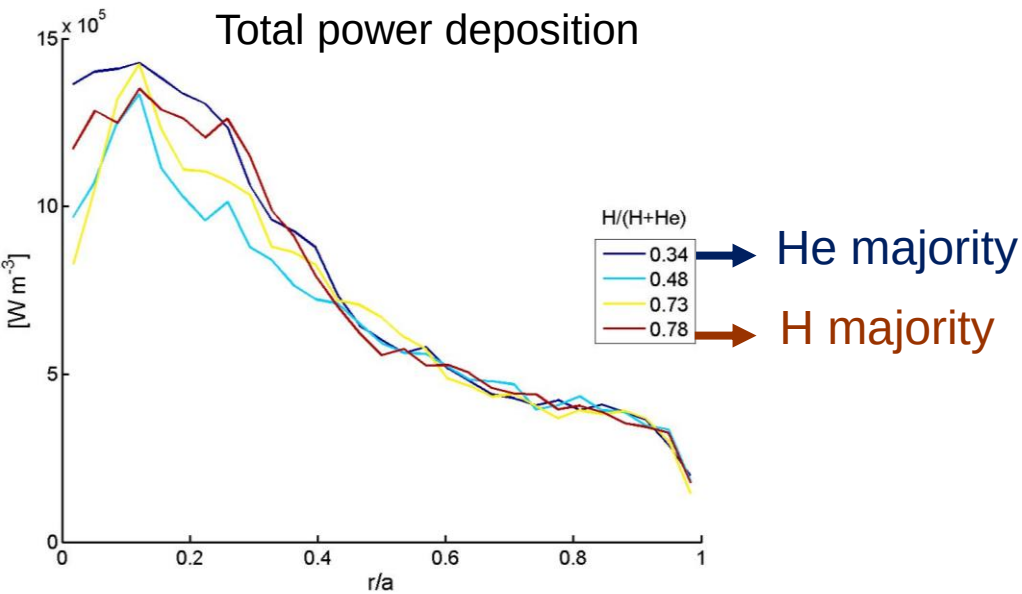
→ H majority

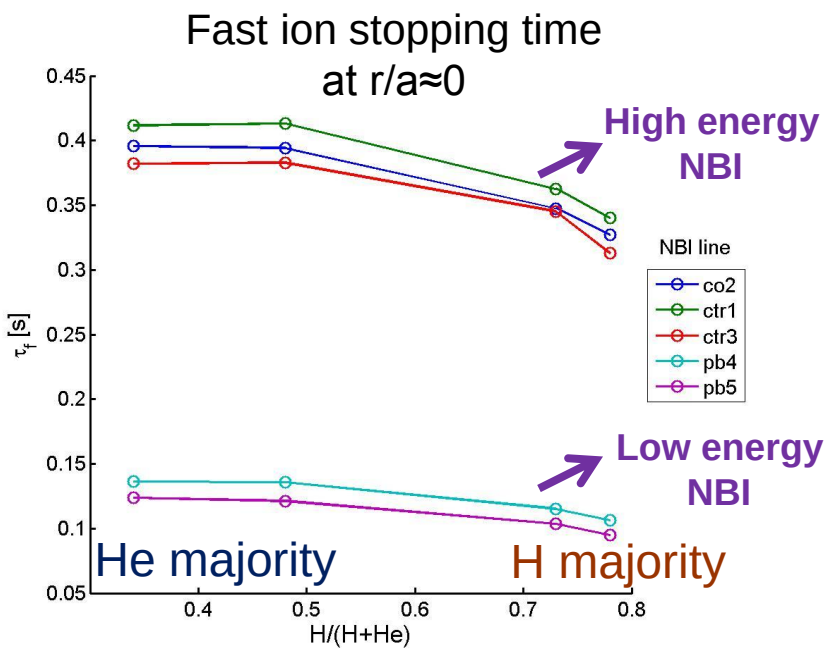
What is the role of NBI heating in the observed T_i increase?

NBI-plasma interaction analysis

Upgraded **FIT3D**[1] NBI-plasma interaction code, stand-alone, steady state approx.

Aim: to understand the role of heat deposition by NBI in different plasmas





Although some differences in fast ion confinement are present, the final NBI power deposition is unaffected by the plasma composition in these cases[2].

Different causes for improved ion confinment?

Ongoing studies for isotope effect: from H to D NBI and plasma in LHD

[1]P. Vincenzi et al., 42nd EPS Conf. on Plasma Physics (Lisbon, Portugal, 2015), P1.150

[2]P. Vincenzi et al., 25th International Toki Conference (Toki-city, Gifu, Japan, 2015), P1.86

Questions?

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Thank you for the attention

Do you have any question?
Curiosity?