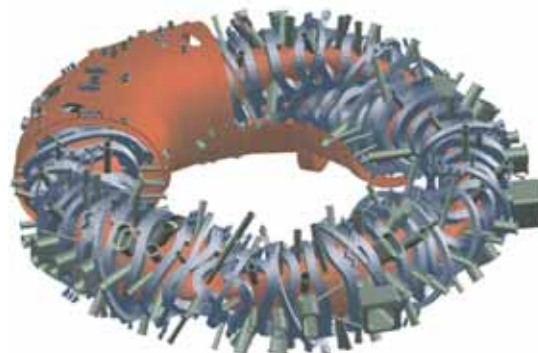
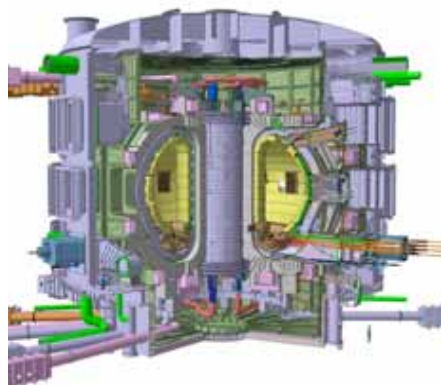


Обзор новых результатов термоядерных исследований в Европе, достигнутых на пути к созданию ИТЭР и ДЕМО



**XLIV Звенигородская Конференция
Звенигород, Московская область, РФ
13 Февраля 2017 г.**

***Джеф ОНГЕНА и др.
Лаборатория Физики Плазмы,
Королевская Военная Академия, Брюссель, Бельгия***

Благодарность: Yevgen Kazakov, Robert Wolf (W7-X), Juan Knaster (IFMIF)

Посвящается памяти Prof. Paul E.M. Vandenplas

Born: 08/12/1931 in Ixelles (Belgium)

Deceased: 20/10/2016 in Woluwe-Saint-Lambert (Belgium)

Civil Engineer and Ph.D. in Physics

Professor Emeritus at Royal Military Academy and Université de Mons-Hainaut (Belgium)

Past mandates:

- *Ex-director of the Association “Euratom-Belgian State” for Controlled Nuclear Fusion*
- *President of the Programme Committee of EURATOM Fusion*
- *Vice-president of the Advisory Committee for the EURATOM Fusion Program*
- *Board member of the Joint European Torus (JET)*
- *President of the Belgian National Committee for Pure and Applied Physics of the Royal Physical Society*
- *President of the Plasma Physics Division of the European Physical Society*
- *Foreign Member of the Ukrainian Higher Education Academy of Sciences*

Prizes and distinctions:

- *Triennial Prize, Alumni Association of the Ecole Polytechnique (RMA)*
- *Prize Georges Vanderlinden of the Belgian Royal Academy of Sciences*
- *Member of Academia Europaea*
- *Grand Officer of the Order of the Crown*
- *Grand Officer of the Order of Leopold II*
- *Officer of the Order of Leopold*
- *Knight*
- *Minerva Prize*





**Nature Physics,
Mei 2016**

“Insight Section”

**66 pages
last minute info !!!**

<http://www.nature.com/nphys/journal/v12/n5/index.html>

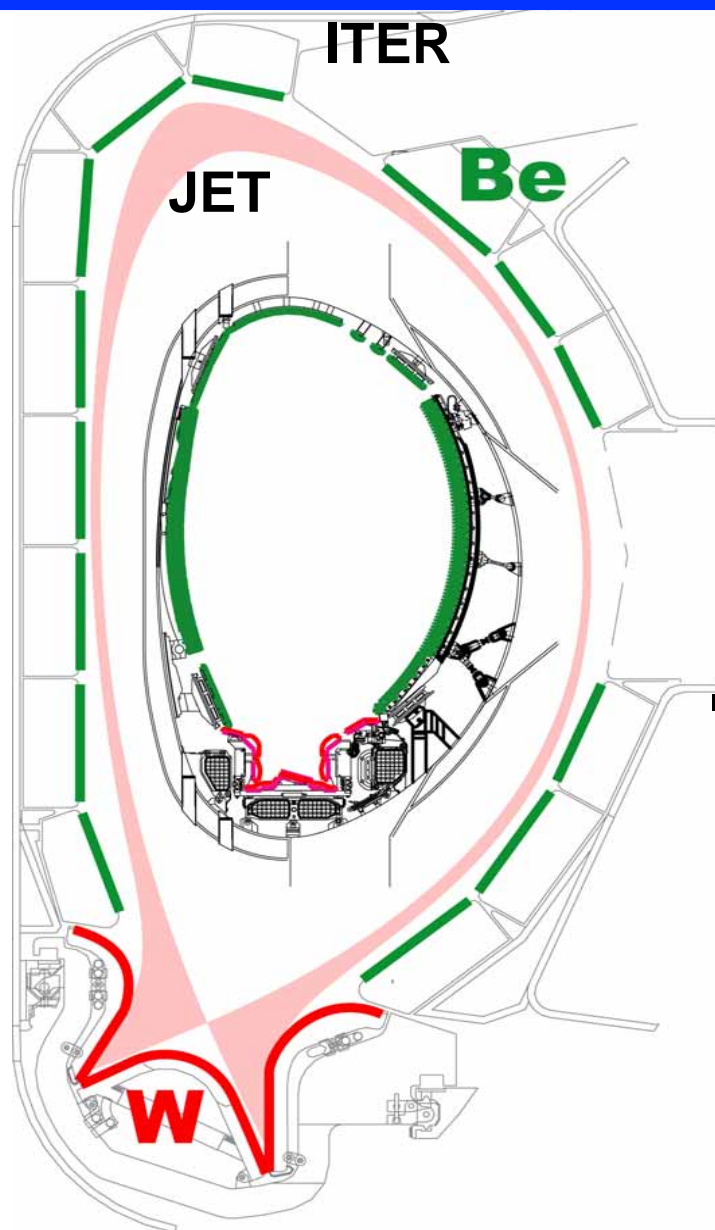
Содержание

- JET – результаты, полученные в ходе последних компаний
- W7-X – результаты, полученные в ходе **первой экспериментальной компаний**
- IFMIF – все прототипные компоненты готовы
 - ожидание решения о начале строительства!
 - $\frac{1}{2}$ IFMIF = DONES – **Бельгия ?**

JET – прогресс на пути к D-T экспериментам и подготовке H-моды для ITER

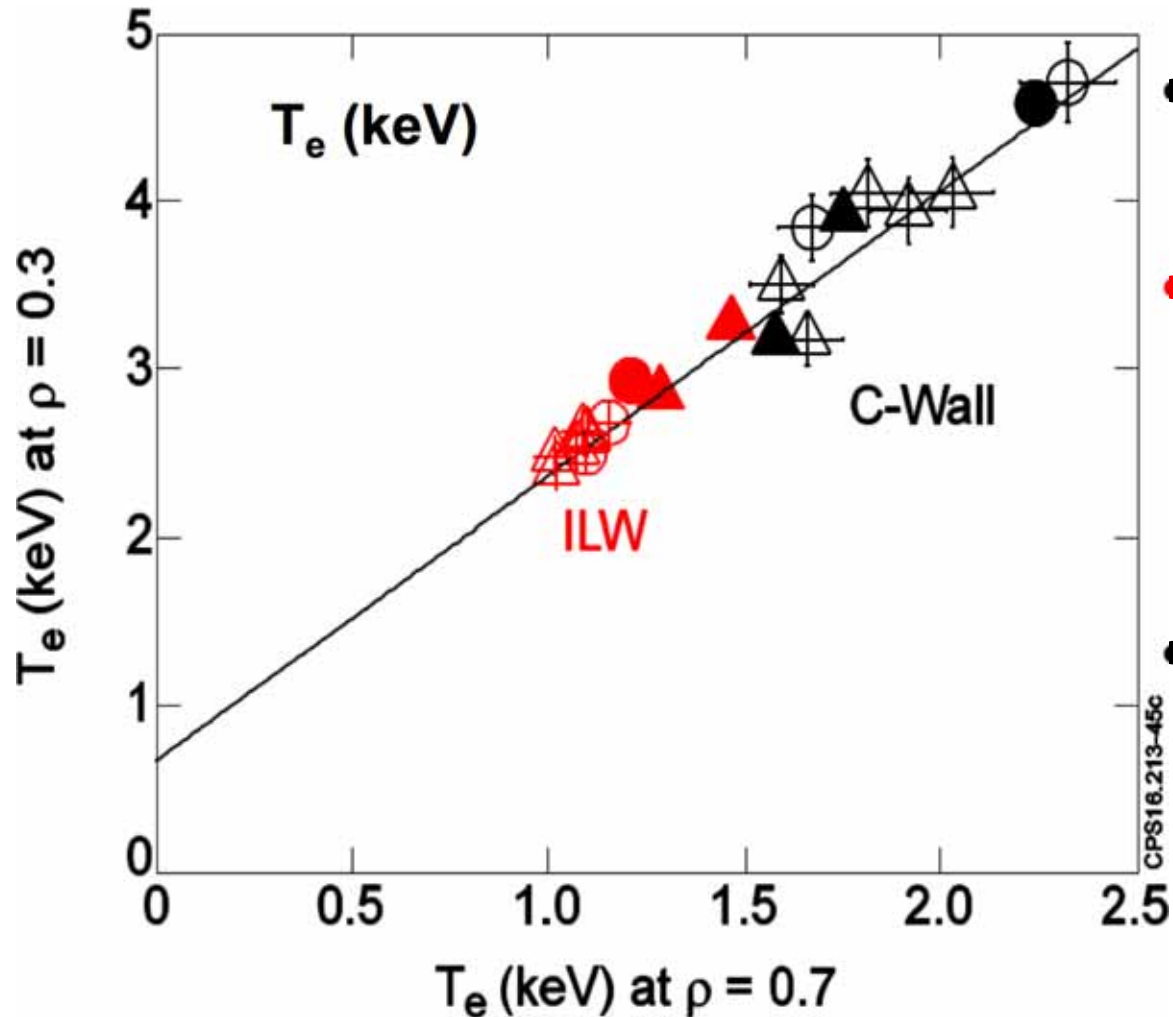
ITER-подобная первая стенка в JET

ITER Like Wall (Be,W) in JET



- ITER-material mix (Be,W) used in a large tokamak
 - “Carbon-free” environment
 - Reduced tritium retention
 - Loss of carbon as main radiator
 - Change in operational space
 - Need for better plasma control
 - Need for heat load mitigation schemes
- Main goals of the ILW experiment
 - I. Demonstrate low fuel retention, migration and possible fuel recovery*
 - II. Demonstrate plasma compatibility with metallic walls*

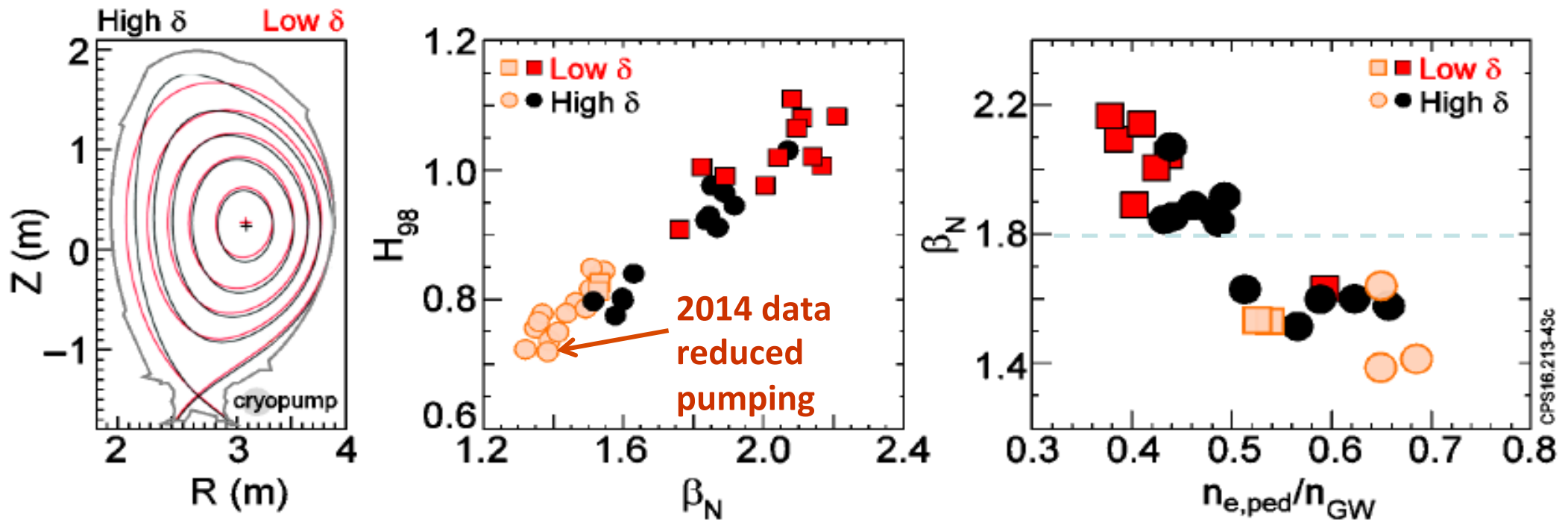
Impact of (Be,W) wall on ITER Q=10 performance



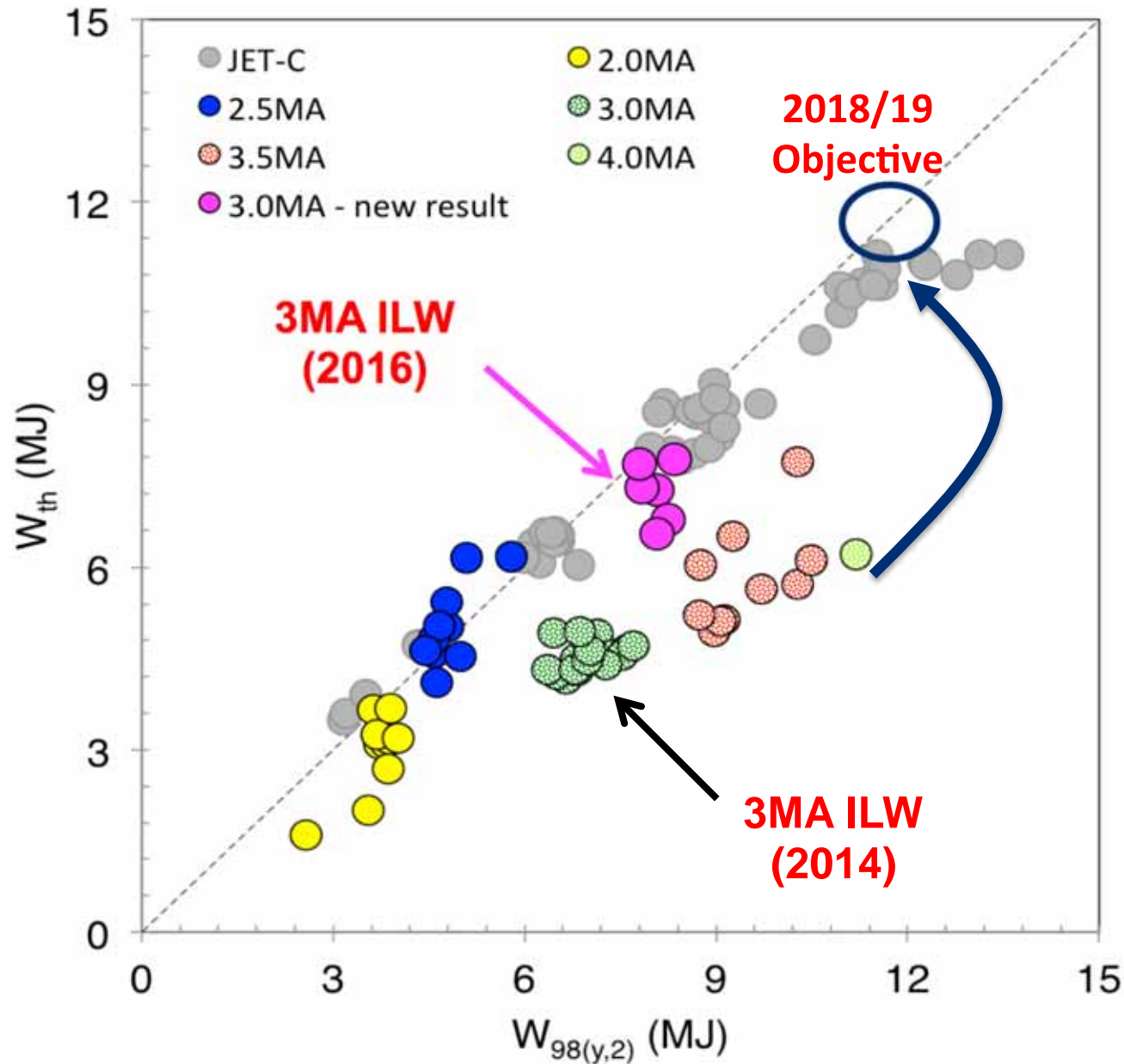
- **Be/W Wall similar core confinement as C-Wall**
- **Edge confinement different:**
 - reduction of electron temperature pedestal
- **Electron transport:**
 - importance of small radial scale ETG instabilities

Combine High-Triangularity and corner pumping

- Stationary (5s) ITER Baseline Operation at high- δ ($\delta_{av} \sim 0.4$) achieved at 2MA/2.2T
 - New high- δ configuration optimized for pumping
 - $H=1-1.1$, $q_{95}=3.2$, $\beta_N=1.8-2.1$, $P/P_{L-H} \sim 2$ but so far $n/n_{GW} \sim 0.5$



Overview latest progress ITER Baseline Operation in JET



Безразмерный анализ в Baseline плазмах с низкой треугольностью

ρ^* scaling

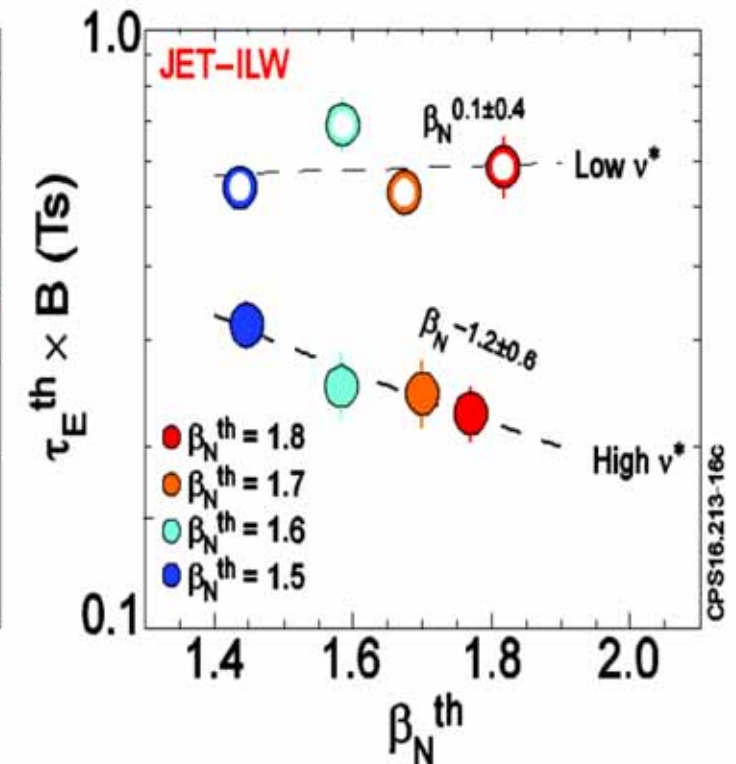
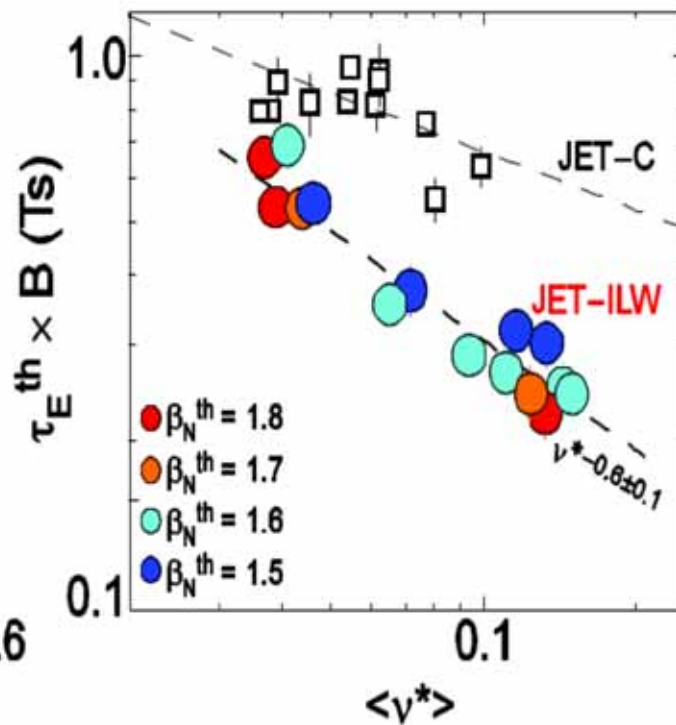
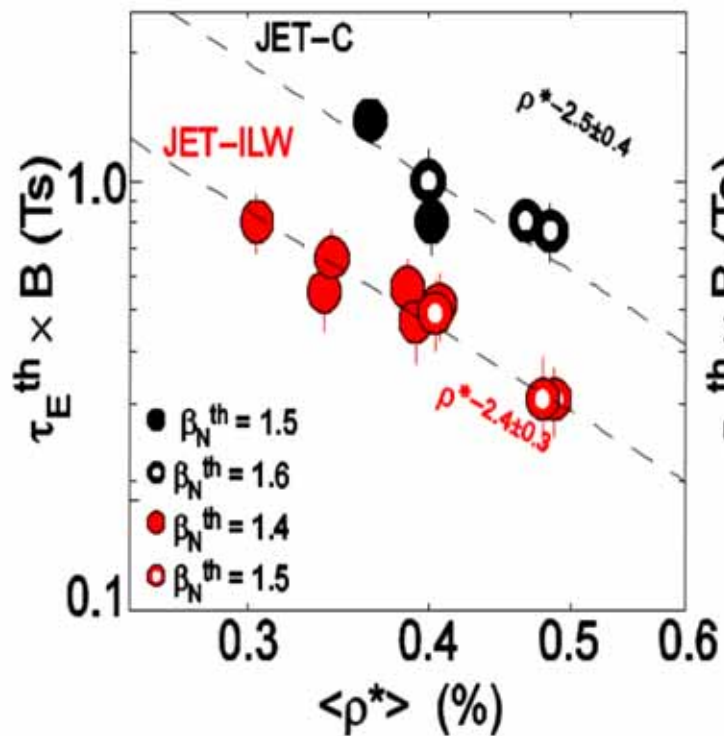
- gyro-Bohm
- no change pedestal limit

v^* scaling

- stronger dependence as ITPA scaling
- pedestal stability improves at low v^*

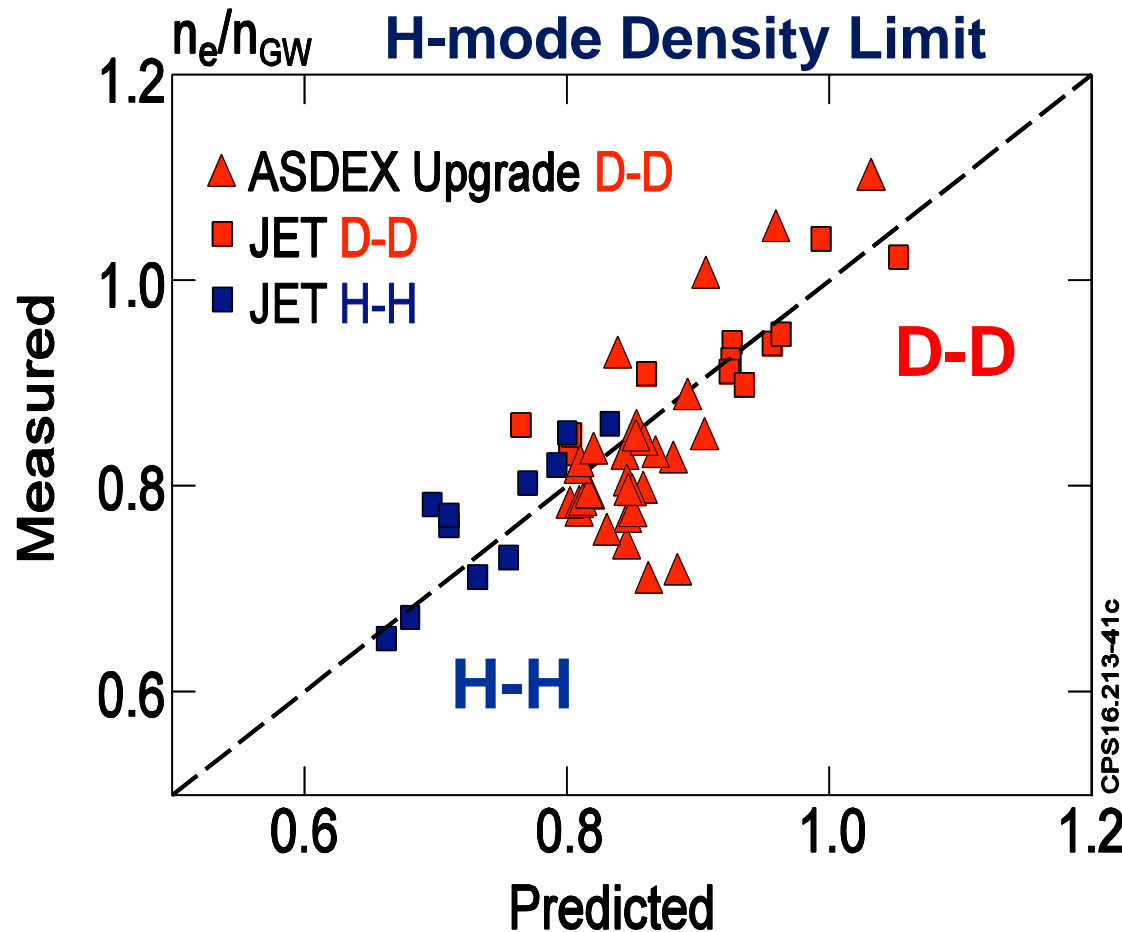
β scaling ($\beta_N \leq 1.8$)

- low v^* : no dependence of transport
- high v^* \rightarrow degradation due to pedestal



H-mode Density limit consistent with Goldston's prediction

[Goldston J of Nuc Materials 2015]

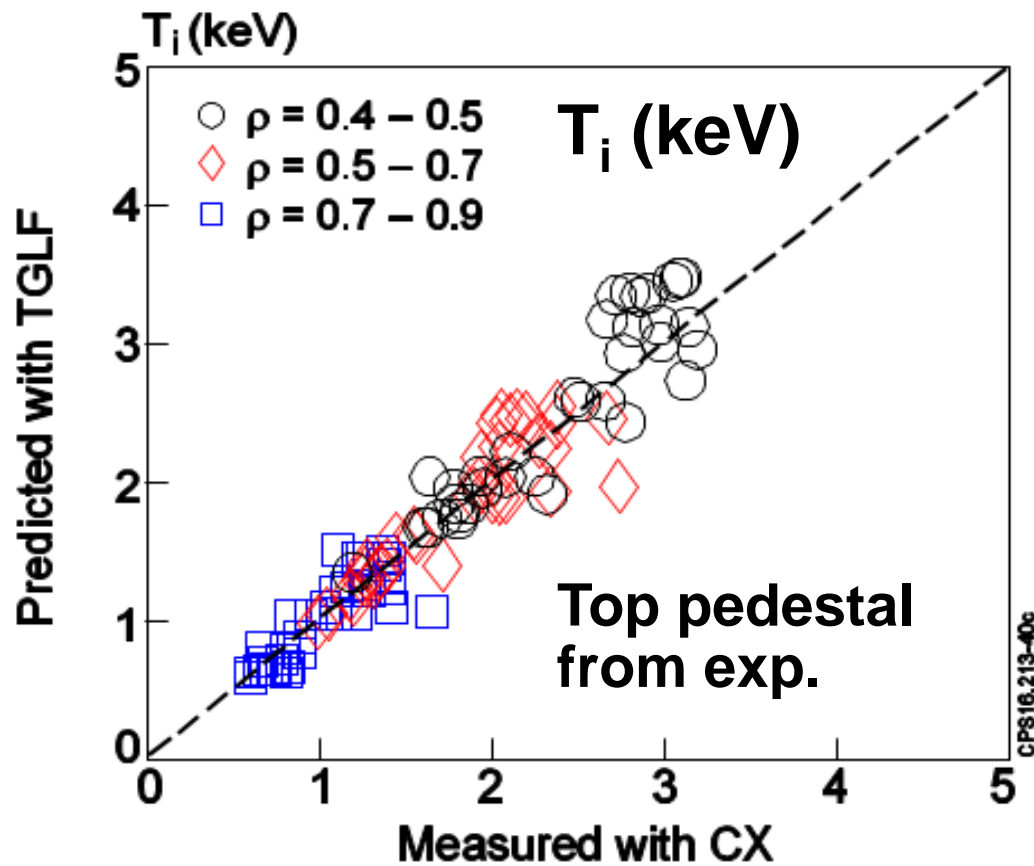


- Mass dependence $\propto M^{9/16}$
- Weak power dependence
- H-mode Density limit
– SOL MHD instability
- Important for D-T operations:
If $M_{\text{eff}} \uparrow$: $P_{\text{L-H}} \downarrow$ & $n_{\text{DL}}/n_{\text{GW}} \uparrow$

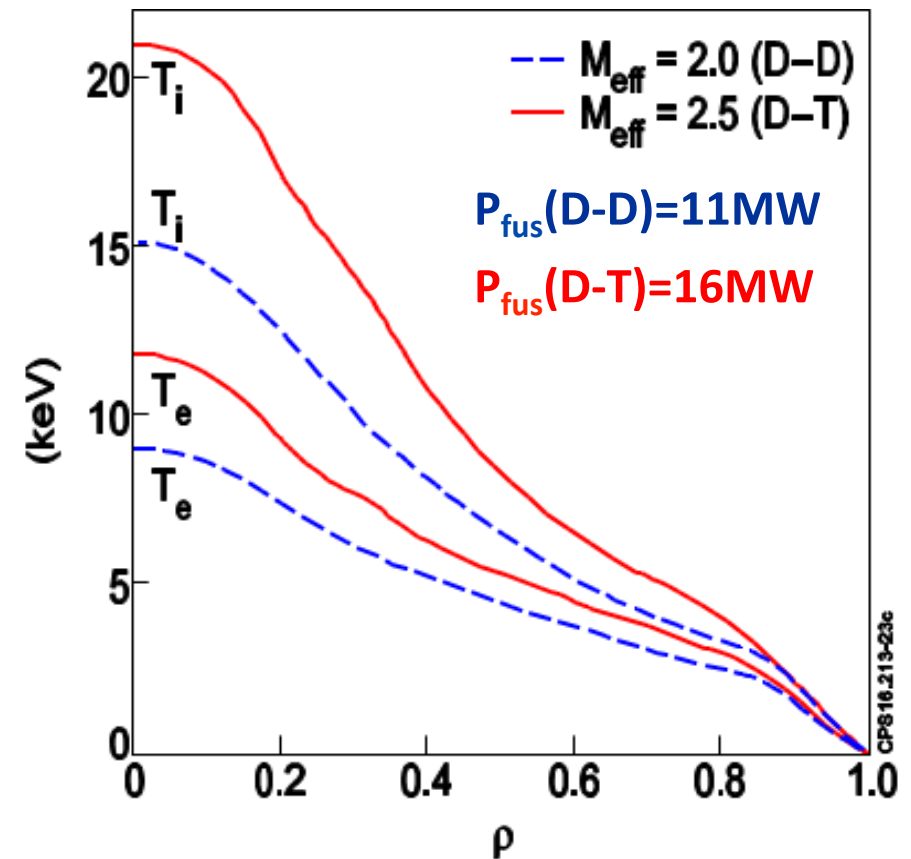
Прогнозы относительно будущих D-T экспериментов

Core transport modelling with TGLF predicts strong isotope effect
Needs experimental validation in T-T and D-T experiments

Validation of TGLF in D-D



Predictions of TGLF for D-T



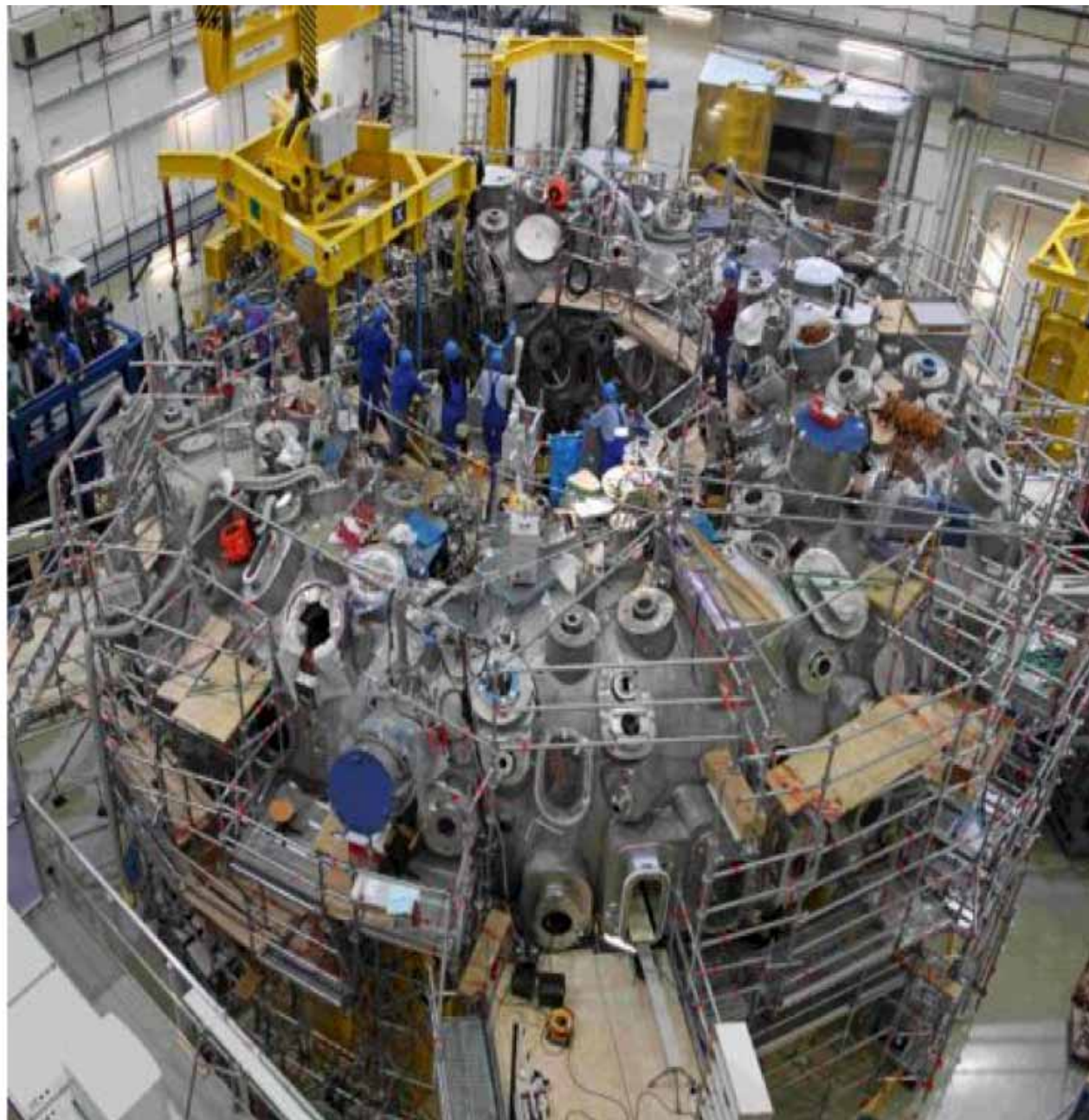
Содержание – Результаты JET

- JET results prepare the ITER active and non-active phase
 - Optimise the path towards ITER Q=10 operation
 - Show importance of edge physics
- JET ITER Like Wall operation and its physics understanding **show the need for an integrated vision**
 - Wall materials + Plasma Surface Interaction + SOL + Pedestal + Core physics are **strongly coupled**
 - No longer a simple scaling to extrapolate
 - More **refined methods needed to extrapolate to ITER**

**Прогресс сталларатопа Wendelstein 7-X,
Институт Макса Планка, Грайфсвальд, Германия**

Wendelstein 7-X: Обзор

Plasma volume **30 m³**
Magnetic field **2.5 T (up to 3 T)**
Superconducting coils **70**
Magnetic field energy **600 MJ**
Cold mass **435 t**
Total mass **735 t**



Wendelstein 7-X: Операционные фазы



OP 2: 2020 ...

Steady-state operation

Actively cooled divertor configuration

$P_{cw} \sim 10 \text{ MW}$

$P_{pulse} \sim 20 \text{ MW (10 s)}$

Technical limit **30 minutes** @ 10 MW

OP 1.2: 2017 / 2018

Uncooled divertor configuration

$P \sim 10 \text{ MW}$

$\int P dt \leq 80 \text{ MJ}$

$\tau_{pulse} \sim 10 \text{ s at 8 MW}$

(... 60 s @ reduced power)

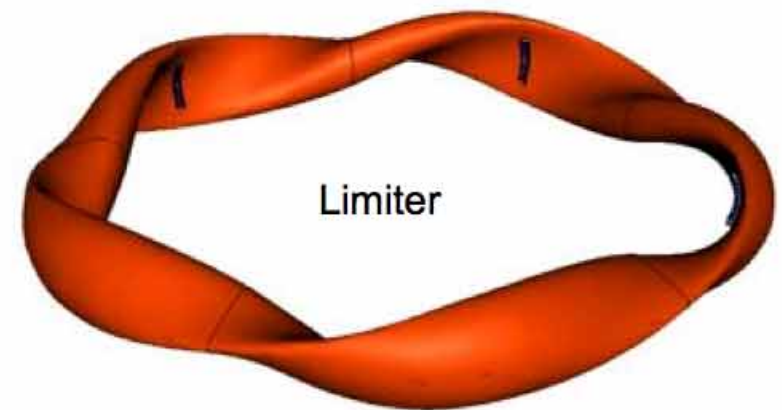
OP 1.1: 2015 / 2016

Limiter configuration

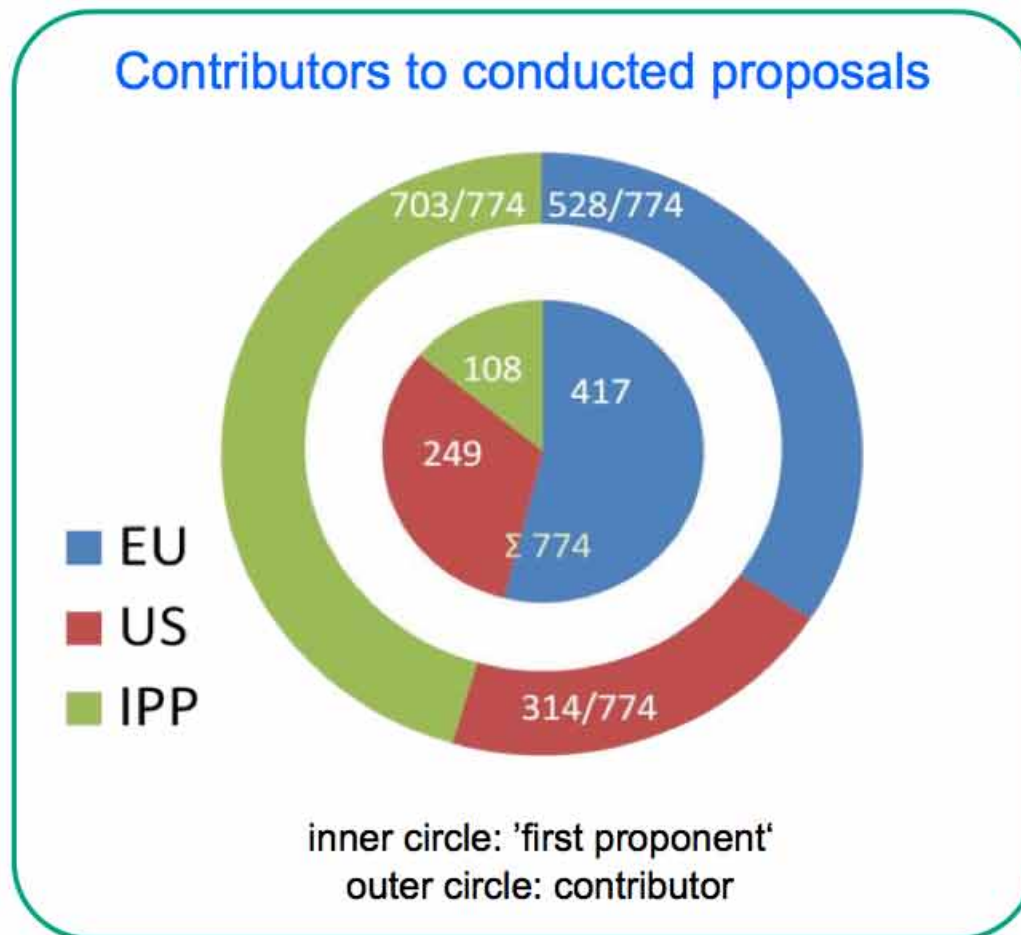
$P < 5 \text{ MW} \rightarrow 4.3 \text{ MW}$

$\int P dt \leq 2 \text{ MJ} \rightarrow 4 \text{ MJ}$

$\tau_{pulse} \sim 1 \text{ s} \rightarrow 6 \text{ s}$



Wendelstein 7-X: Large international collaboration



- 402 out of 843 plasma experiments (discharges) with physics proposals
- 774 proposals conducted in the 402 physics programs

Wendelstein 7-X: Первая экспериментальная кампания: достигнуты все заявленные цели

OP 1.1 priorities: Integral commissioning and first plasma operation

1. Integral commissioning of all systems needed for successful plasma operation ✓
2. Existence of closed flux surfaces all the way to the limiter (at B=2.5 T) ✓
3. Measurement and adequate reduction of B_{11} field errors (✓)
4. Reliable ECRH plasma startup scenario in He ✓
5. Basic ECRH interlocks and safe operation scenarios: $\int P dt \leq 2$ MJ ✓
6. Basic impurity content monitoring ✓
7. Central $T_e > 1$ keV at $n_e > 5 \cdot 10^{18} \text{ m}^{-3}$ in at least 10 discharges in He ✓

$$P_{ECRH} \leq 4.3 \text{ MW}$$

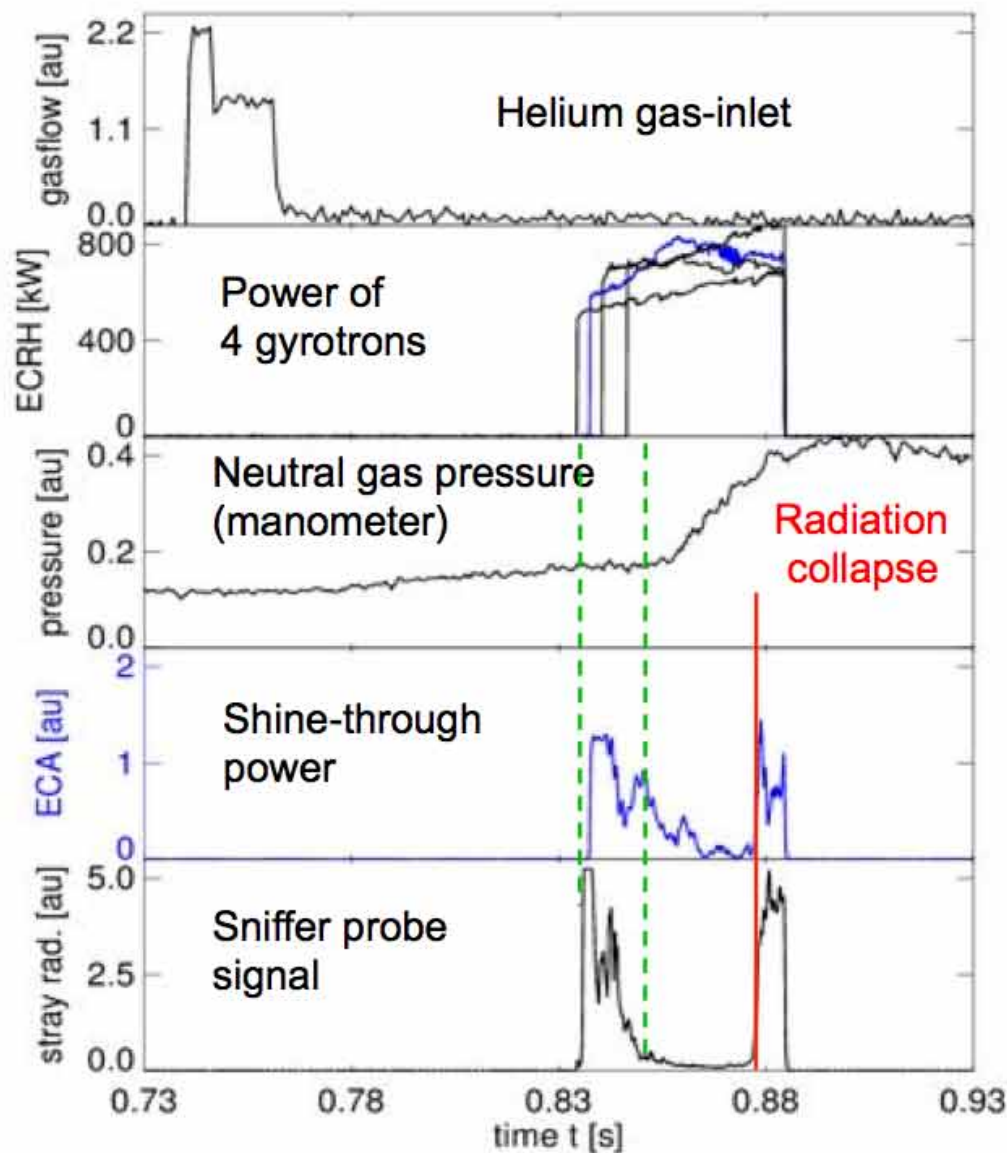
$$4 \text{ MJ} / 6 \text{ s}$$

$$T_e \sim 10 \text{ keV}$$
$$T_i \leq 2 \text{ keV}$$

$$\text{He} \leq 8 \cdot 10^{19} \text{ m}^{-3}$$
$$\text{H} \leq 2 \dots 3 \cdot 10^{19} \text{ m}^{-3}$$

Confirmation of optimization goals of W7-X will be done in later operation phases

Wendelstein 7-X: Создание плазмы

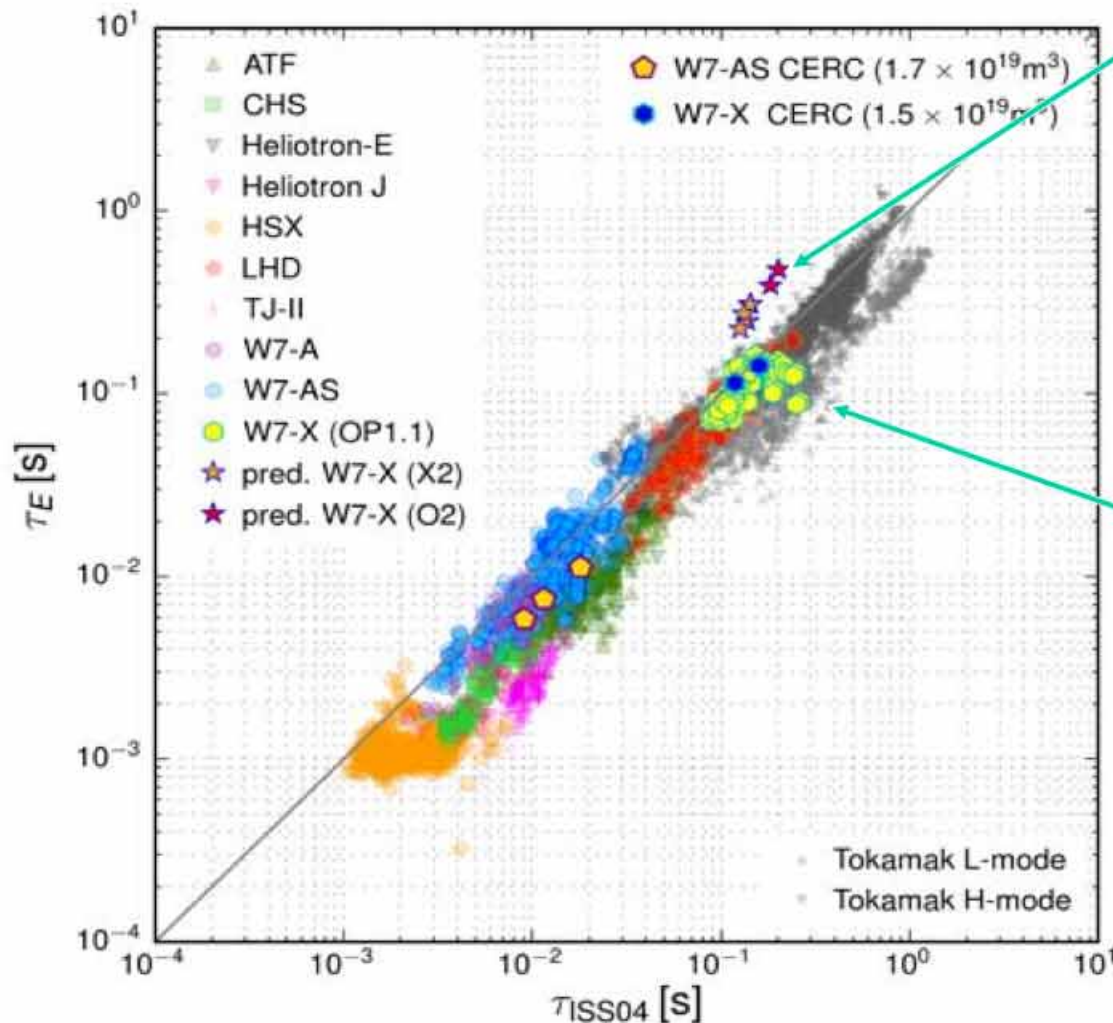


- Plasma break-down within 10ms
- Hundreds of short ECRH cleaning discharges (3 days corresponding to about 4 sec plasma operation)



- ⇒ discharge length extended to ~50ms
- ⇒ With more pulses and glow discharge cleaning, eventually 6 seconds

Wendelstein 7-X: Удержание



Optimized confinement time as predicted for W7-X ion-regime ($\chi_{e,1/v} \sim \epsilon_{\text{eff}}^{3/2}$)

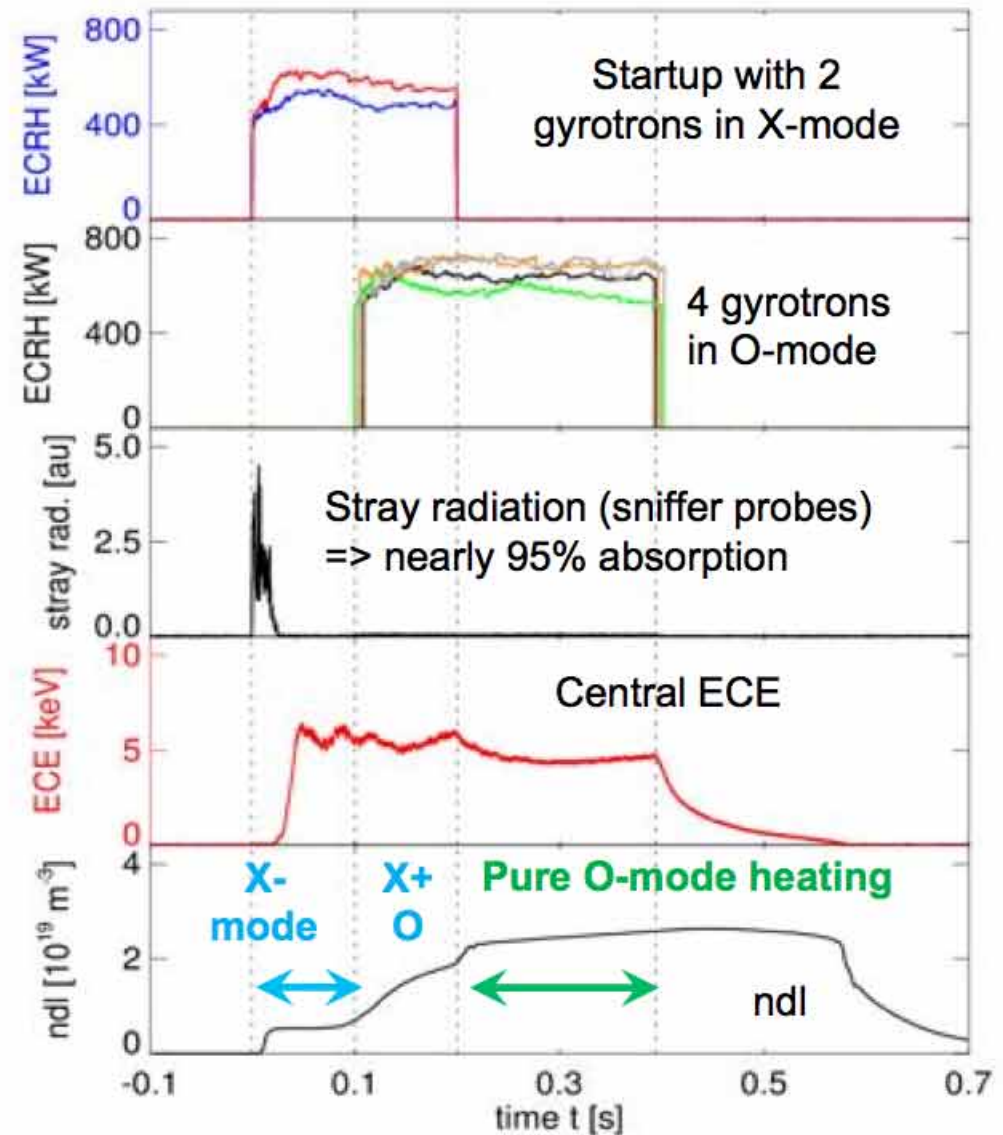
Confinement times during 1st W7-X campaign

- Best plasmas lie on ISS04-scaling
- Only 16 days of hydrogen operation
- Conditioning of wall was still ongoing; impurity issues

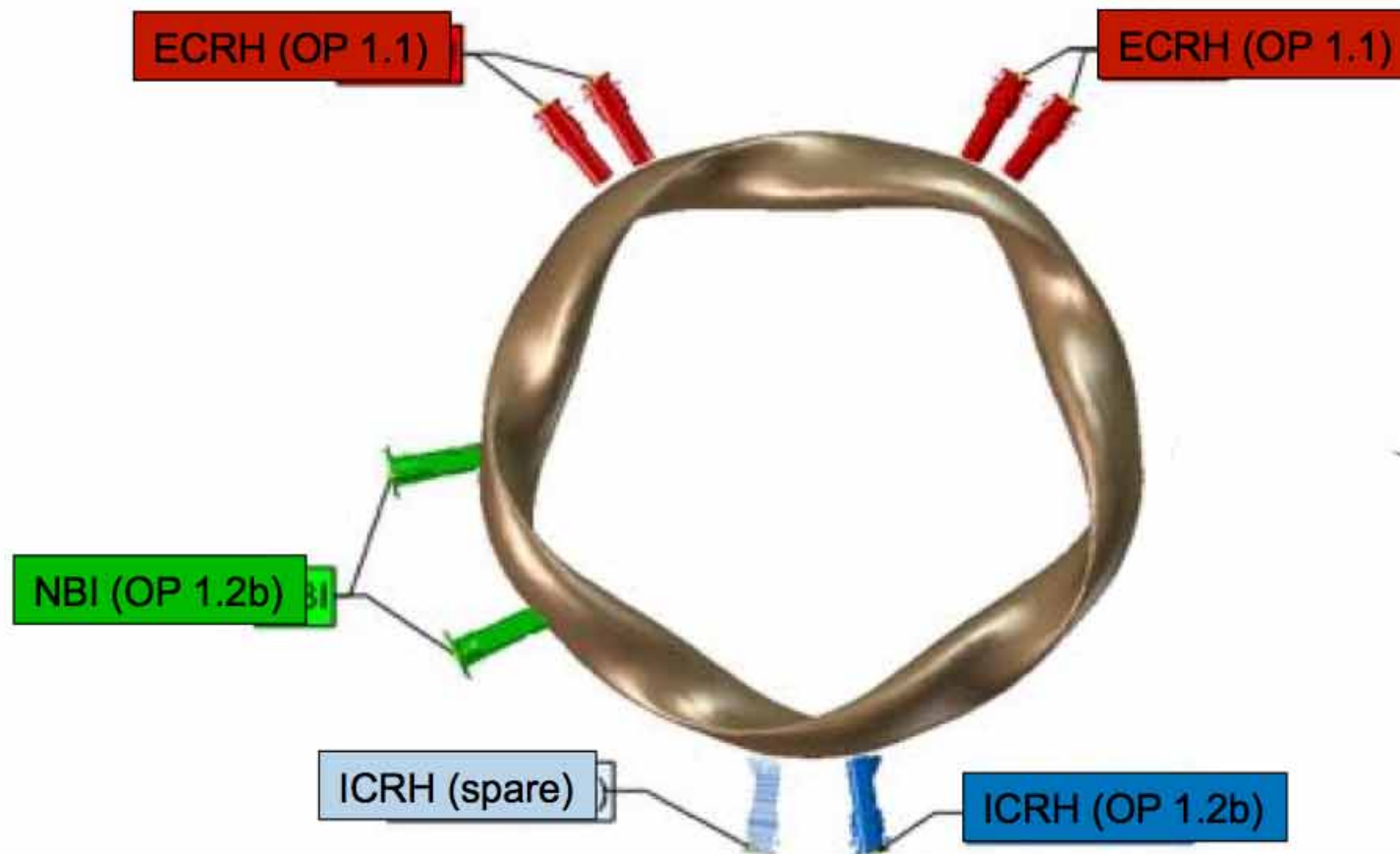
$$\tau_E^{\text{ISS04}} = 0.134 a^{2.28} R^{0.64} P^{-0.61} \bar{n}_e^{0.54} B^{0.84} t_{2/3}^{0.41}$$

Демонстрация O2-ЭЦР нагрева плазмы

- Proof-of-principle for high-density operation with ECRH in future operation phases
- Plasma start-up in X2-mode
 - X2-cutoff at $n_e = 1.2 \cdot 10^{20} \text{ m}^{-3}$
- For $T_e \geq 5 \text{ keV}$ simultaneous X2- and O2-heating
- Finally, sustainment of plasma with only O2-heating
 - O2-cutoff is at $2.4 \cdot 10^{20} \text{ m}^{-3}$



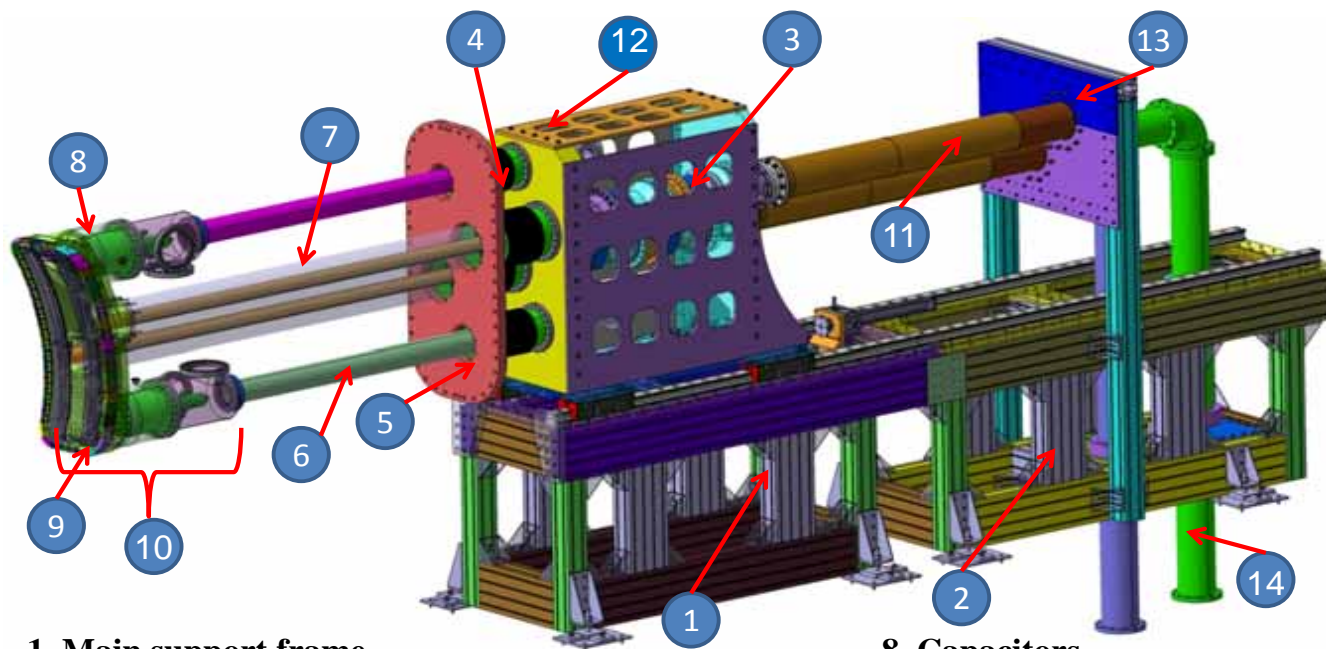
Wendelstein 7-X: Системы нагрева плазмы



Wendelstein 7-X: Системы нагрева плазмы

Method	OP 1.1	OP 1.2	OP 2
ECRH steady state 140 GHz 2.5 T	5 MW X2 LFS launch (front steering)	9 MW X2 / O2 LFS & HFS launch (front & remote steering)	9 MW X2 / O2 / OXB LFS & HFS launch (front & remote steering)
NBI pulsed 55 keV (H) 60 keV (D)		7 MW (H)	10 MW (D) 7 MW(H)
ICRH pulsed 25 – 38 MHz		2 MW ³ He, H minority	4 MW ³ He, H minority
		Upgrade of power supplies	...

Система ICRH для W7-X проектируется бельгийско-немецкой группой (Брюссель-Юлих)



1. Main support frame

2. Alignment and integration support

3. RF vacuum feedthroughs

4. Edge welded bellows

5. Cryostat flange

6. Service tubes

7. Coaxial conductors and mechanical support

8. Capacitors

9. Antenna head

10. Antenna box

11. Coaxial line stretcher

12. Movable antenna unit

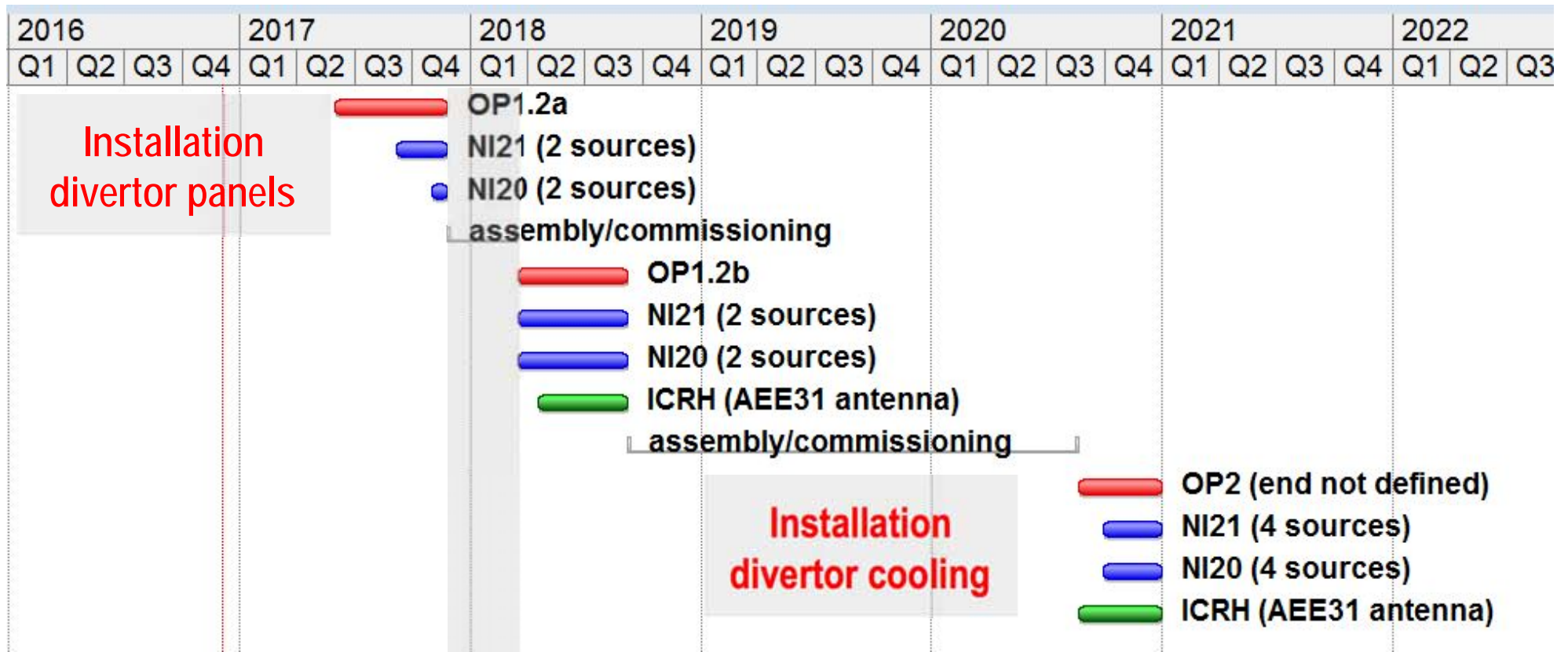
13. Coaxial line interface

14. Fixed coaxial lines

- Generation of fast ions $\sim 100\text{keV}$ at high plasma density $\sim 2 \times 10^{20}\text{m}^{-3}$
- TEXTOR RF generators in Greifswald ($2 \times 2\text{MW}$)
- Using 3 ion heating scenario (first tests in C-Mod, oktober 2015)

Reference: J.Ongena et al., Physics of Plasmas **21**, No. 6, (2014) 061514

Wendelstein 7-X: план работы



OP1.2a: ~May-Dec 2017

OP1.2b: ~March-Sept 2018

OP 2: : ~Sept 2020 - ...

**Экспериментальное подтверждение ICRH нагрева
плазмы на основе сценария с тремя сортами ионов на
JET**



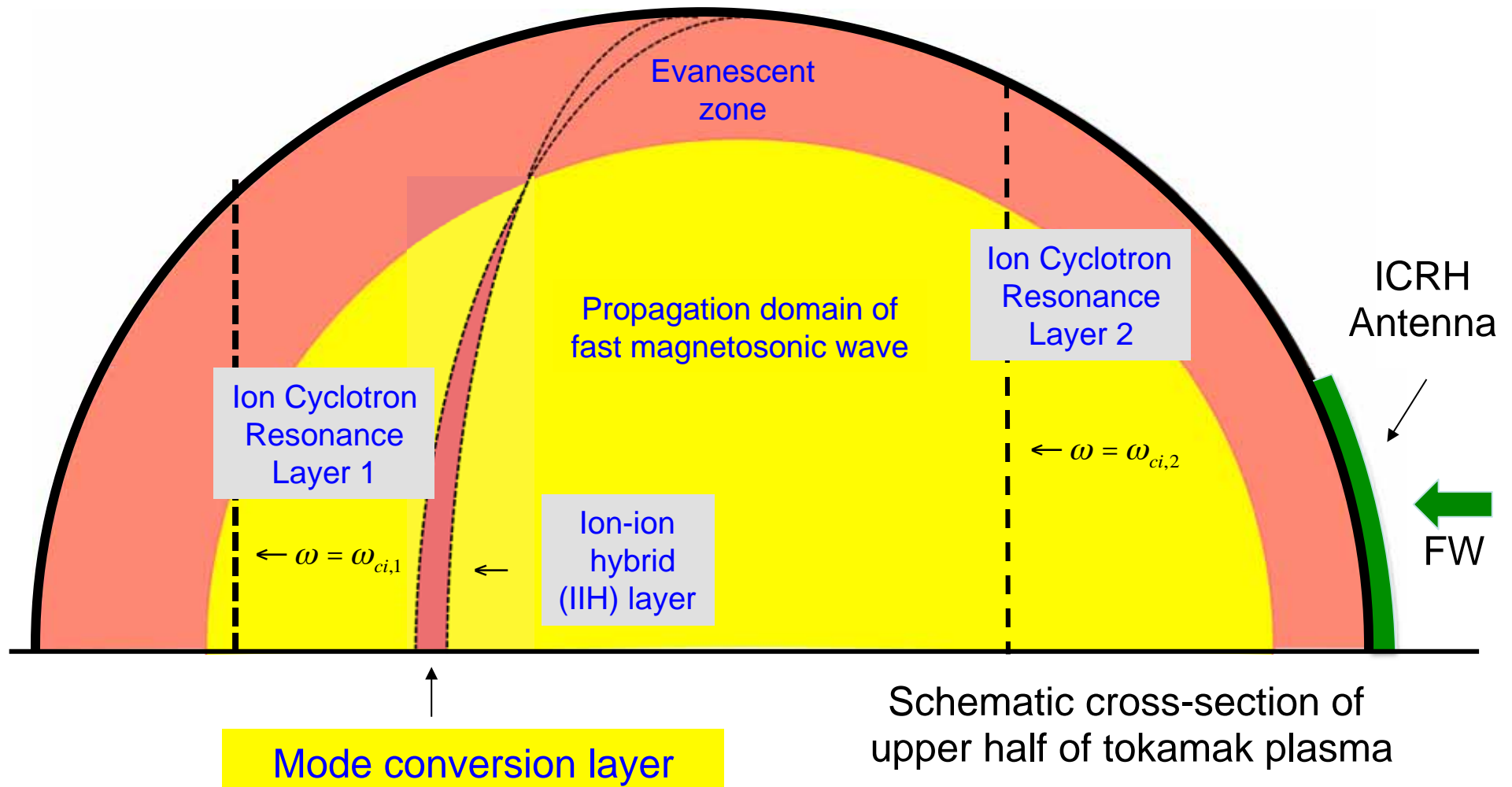
**ICRH in H-(³He)-D
JET experiments:**

H-D mixture + ³He < 1%

**$B_0 = 3.2\text{T}$, $I_p = 2\text{MA}$,
 $f = 32.5\text{MHz}$, $n_{e0} \approx 4 \times 10^{19} \text{ m}^{-3}$**

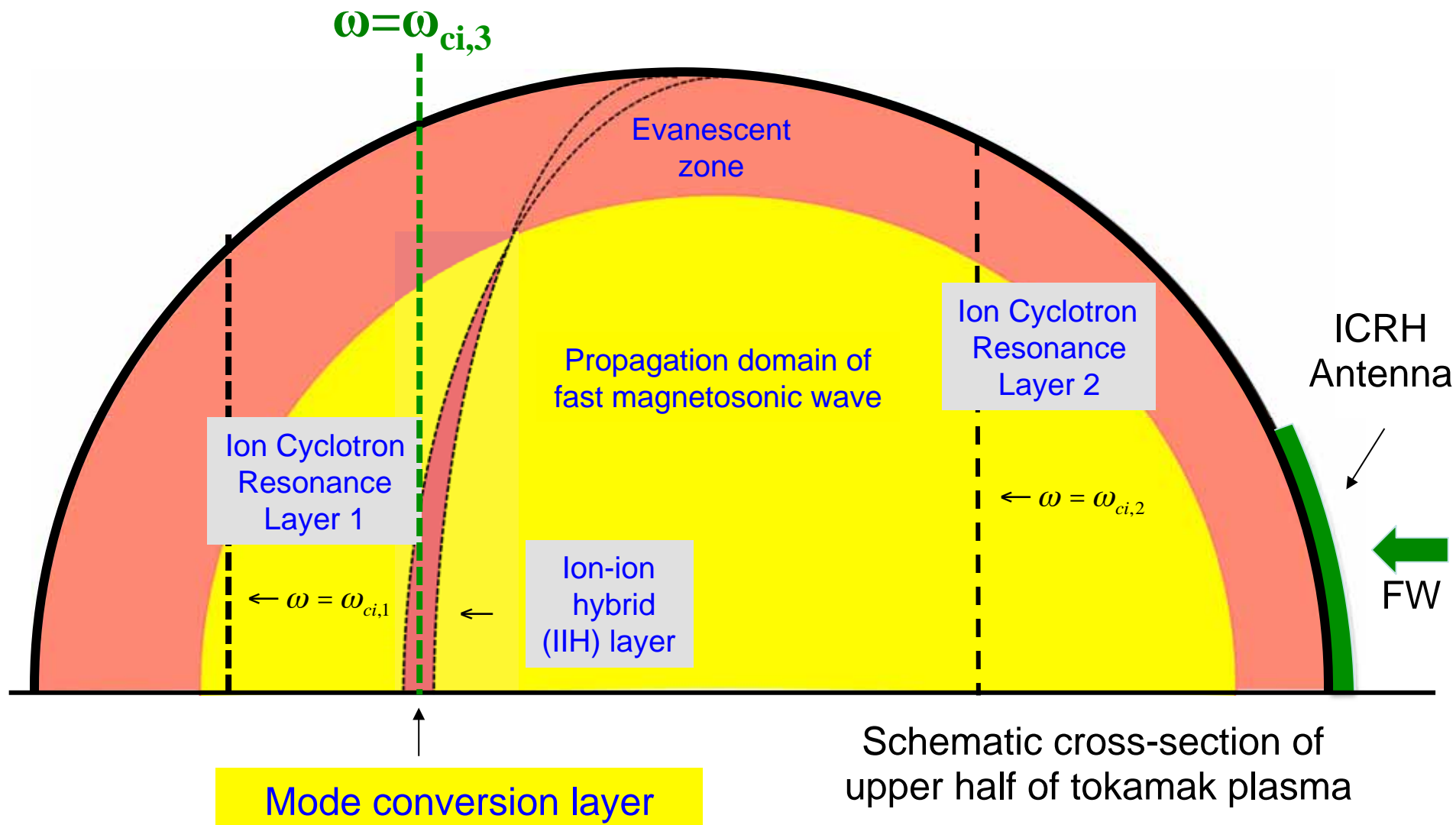
Schematic diagram of ICRH wave absorption

Traditional scheme for two ion plasma

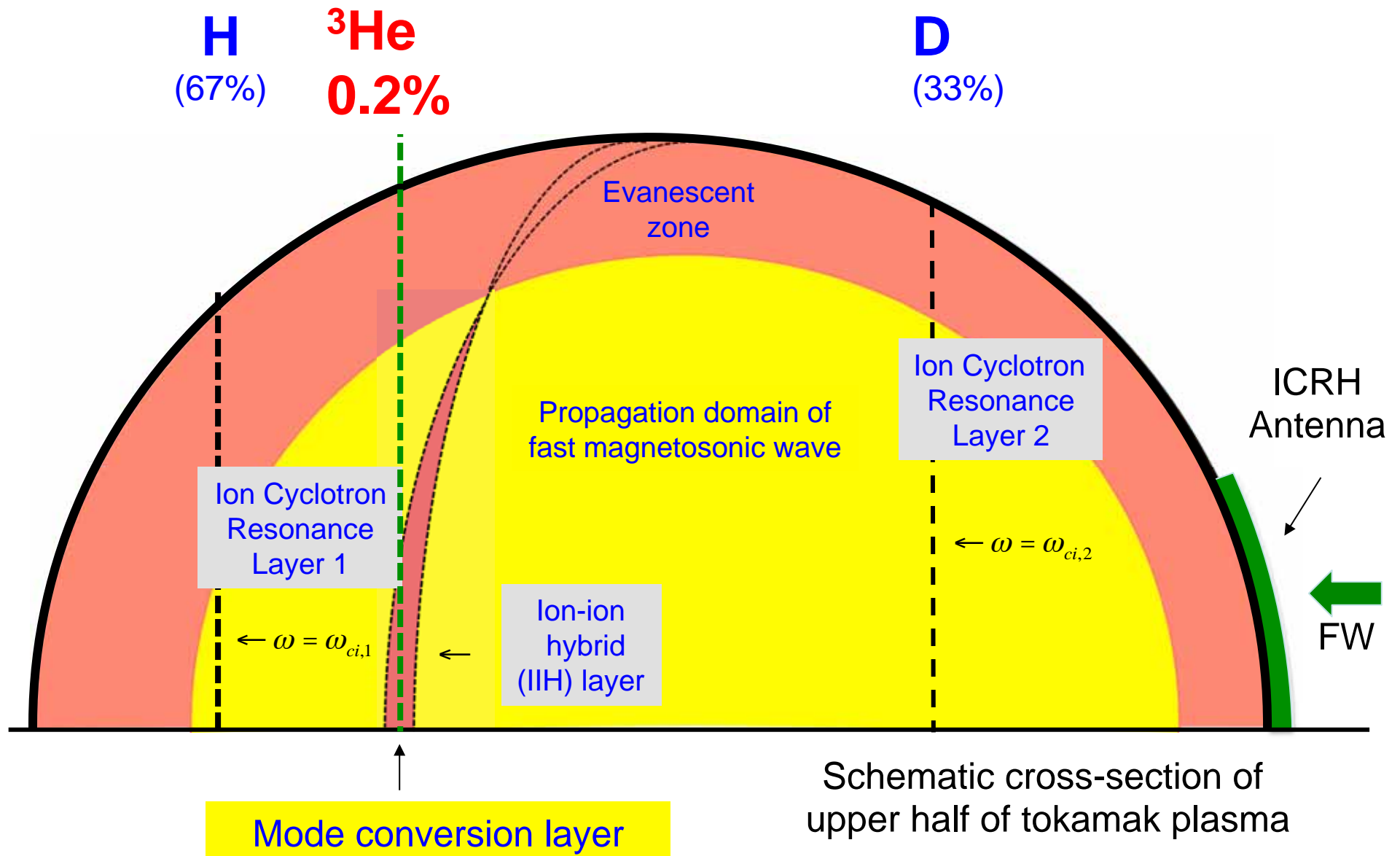


Schematic diagram of ICRH wave absorption

Add 3rd ion with resonance in Mode Conversion layer
→ 3 ion scheme !



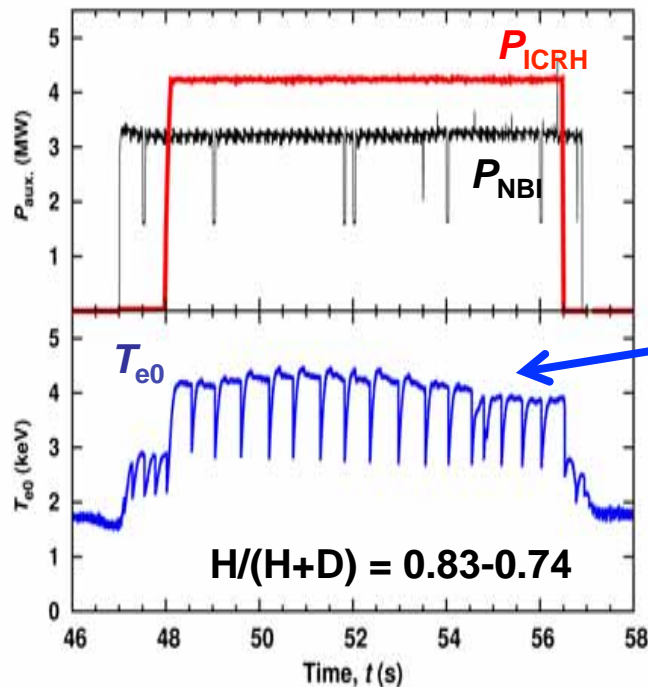
Schematic diagram of ICRH wave absorption



Н-(³He)-D в JET

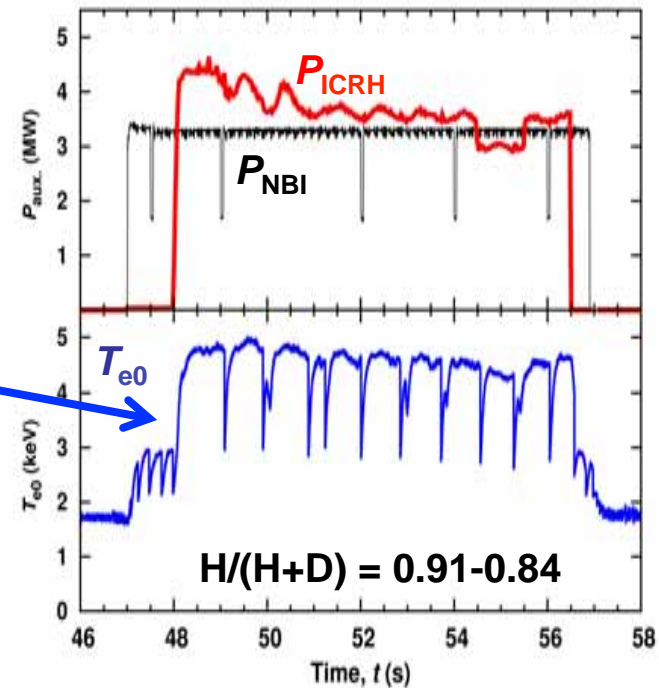
Стабилизация пилообразных колебаний

#90752: $X[{}^3\text{He}] \sim 0.2\text{-}0.3\%$ (dipole ICRF phasing)



Fast ³He particles
→ Long sawteeth !

#90755: $X[{}^3\text{He}] \sim 0.1\text{-}0.3\%$ (+ $\pi/2$ ICRF phasing)



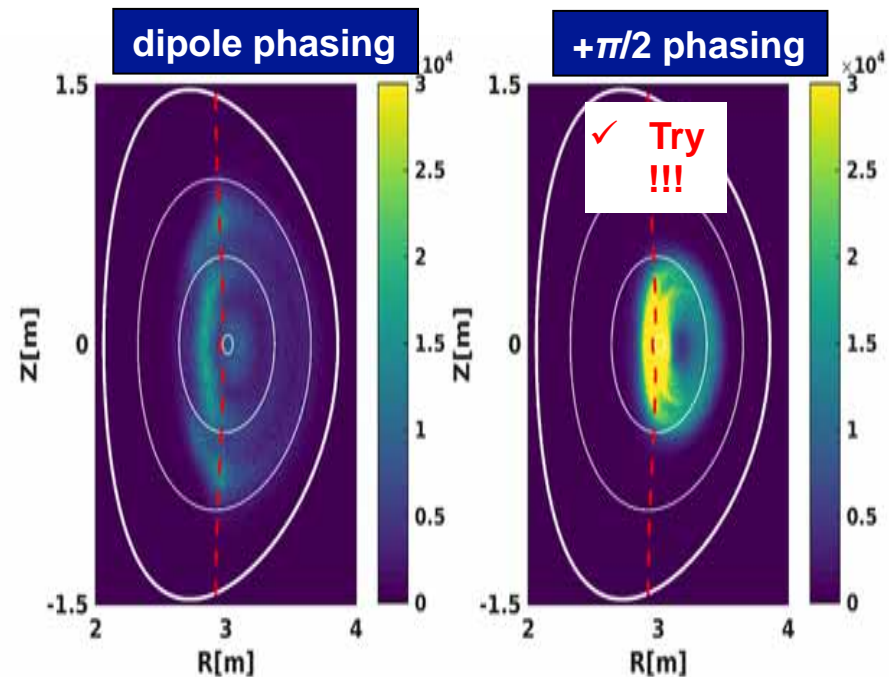
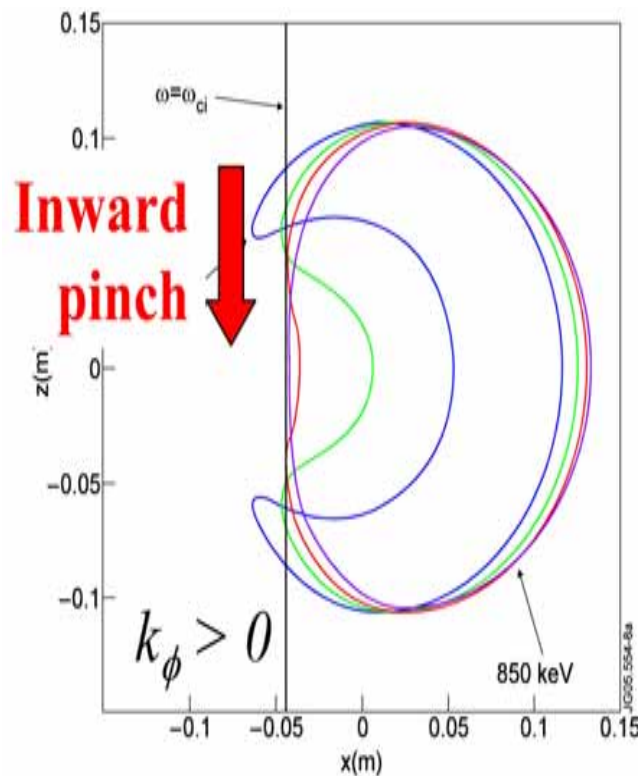
Efficient plasma heating at ³He concentrations as low as ~0.2% successfully demonstrated

Использование $+\pi/2$ фазировки ВЧ антенны численные расчеты

Улучшение генерации быстрых ионов в центре плазмы

RF-induced pinch effect: inward displacement of the turning point for waves launched in the co-current direction

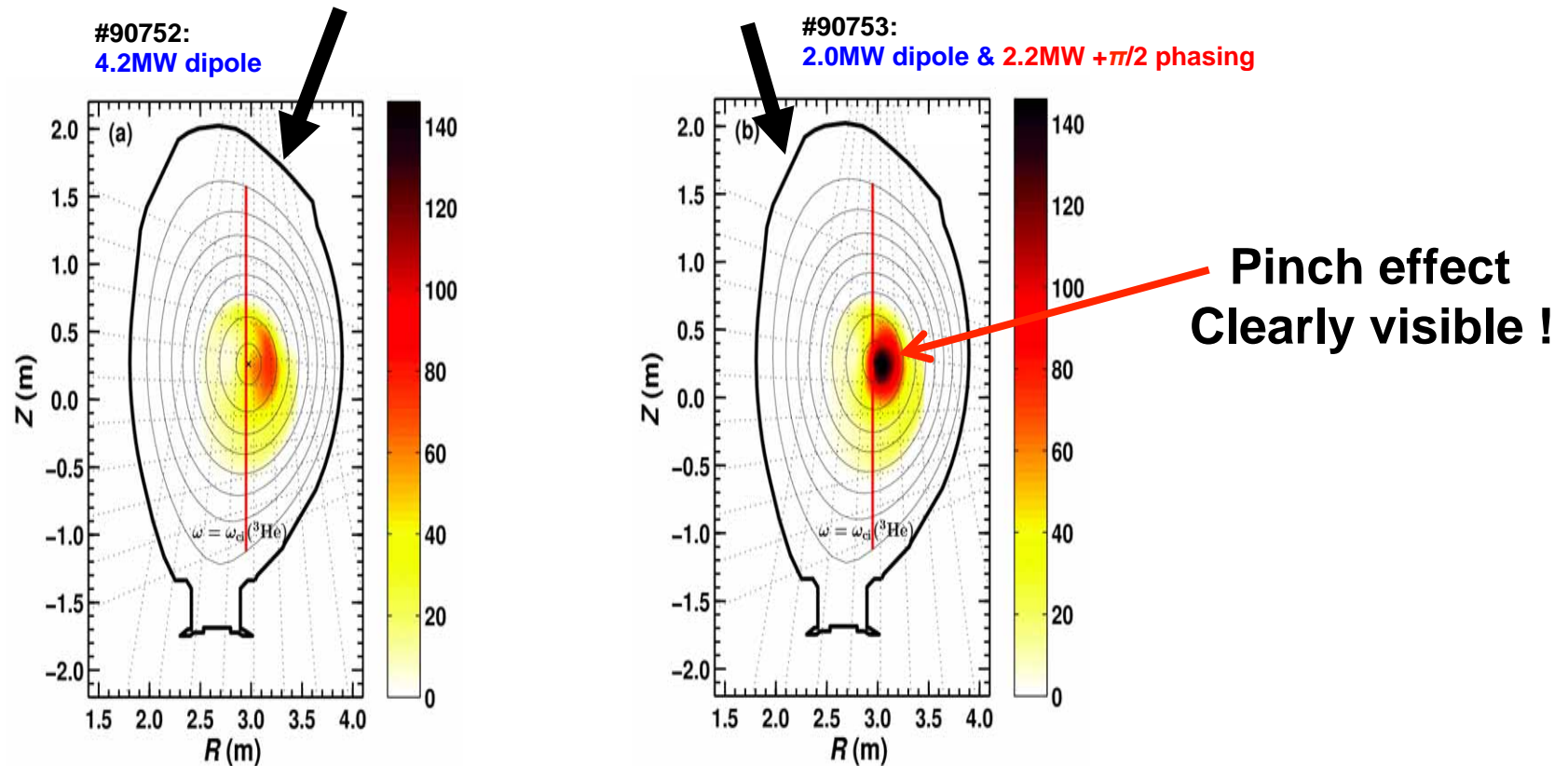
(L.-G. Eriksson et al. PRL (1998); M.J. Mantsinen et al., PRL (2002))



Использование $+\pi/2$ фазировки ВЧ антенны: экспериментальные результаты

Визуализация популяции быстрых ионов в плазме с помощью томографической реконструкции гамма-излучения

Same main plasma parameters

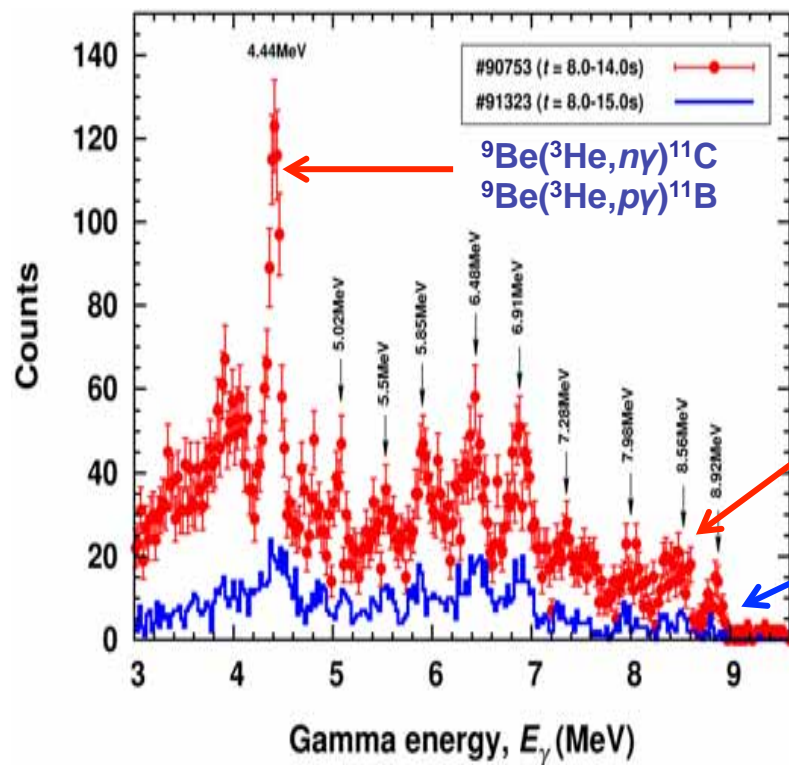


* #90752 (left) and #90753 (right): $H/(H+D) = 0.84 \rightarrow 0.75$, $X[{}^3\text{He}] \approx 0.2-0.3\%$, $P_{RF} = 4.2\text{MW}$

Наблюдение высокоэнергетических ионов ^3He с помощью анализа гамма-излучения

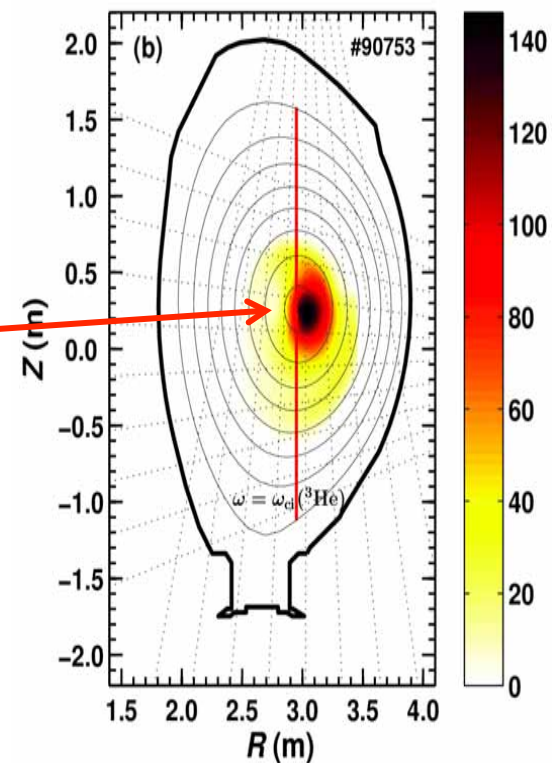
Низкая концентрация ионов ^3He \rightarrow увеличивается ВЧ мощность, поглощаемая отдельным резонансным ионом ^3He

Томографическая реконструкция гамма-излучения: локализация высокоэнергетических ионов ^3He в центре плазмы



H-(^3He)-D
4.2MW ICRH

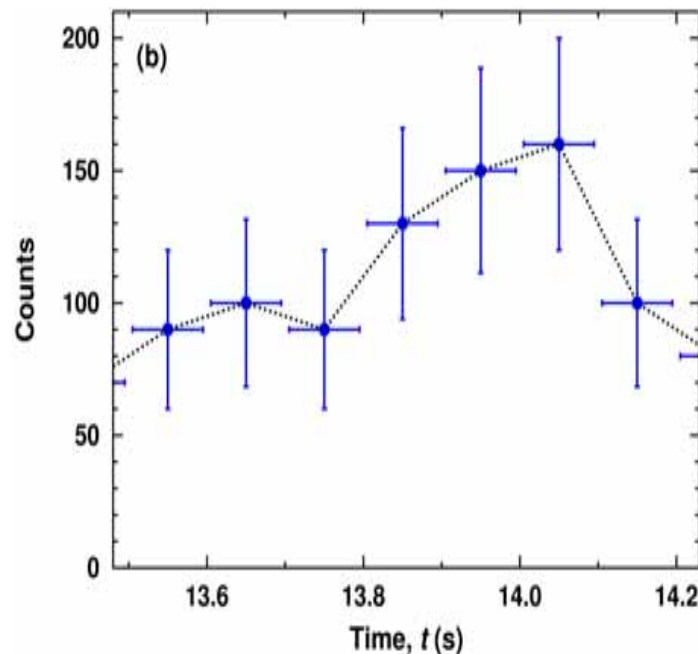
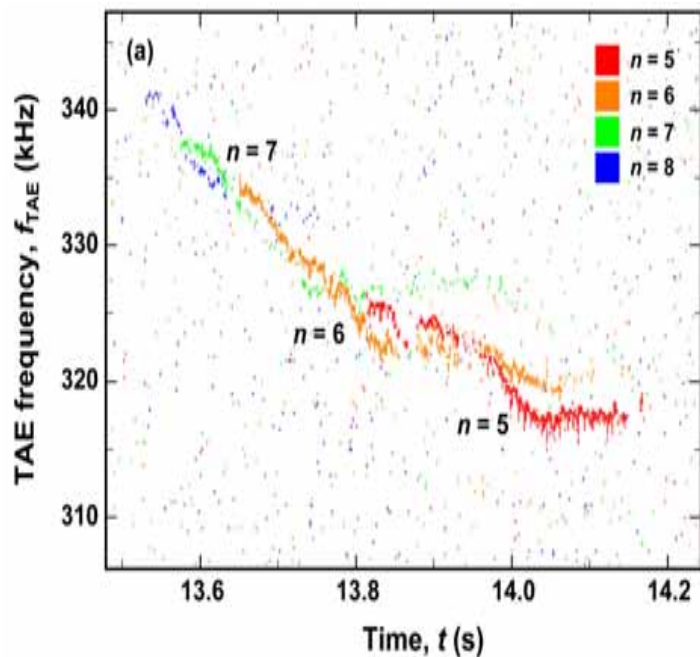
(^3He)-H
7.5MW ICRH



Multiple gamma-lines with $E_\gamma > 4.44\text{MeV}$ (excitation requires $\sim 2\text{MeV}$ ^3He ions)

Возбуждение ТАЕ (тороидальные альфвеновские моды): независимое подтверждение генерации ионов с МэВ-энергиями

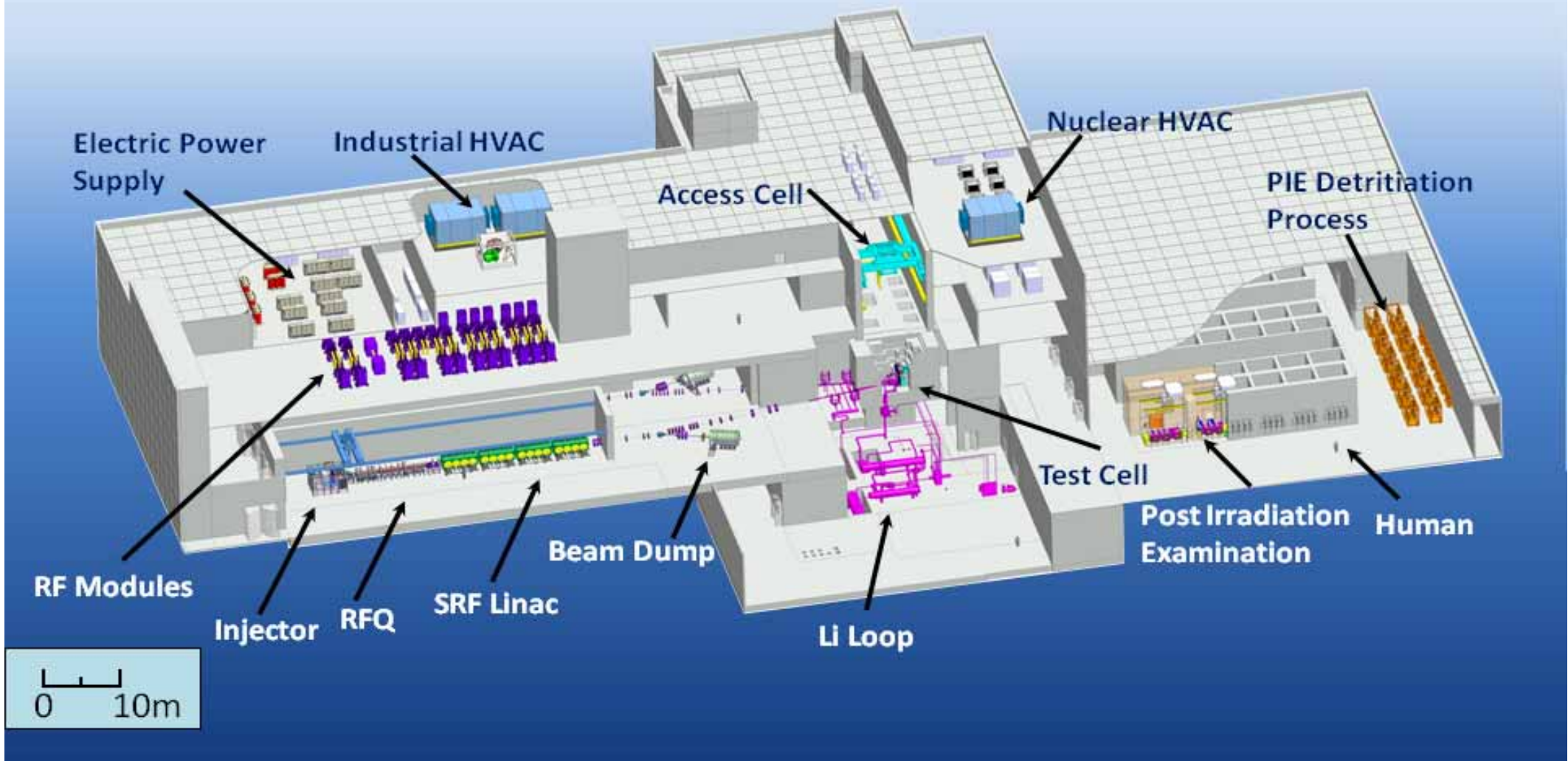
#90758: $P_{RF} = 4.4\text{MW}$, $+\pi/2$ phasing, $\text{H}/(\text{H}+\text{D}) \sim 0.90$, 0.2–0.4% of ^3He



- Toroidal Alfvén eigenmodes (TAEs) excited when part of RF power in $+\pi/2$ phasing
- ^3He energy estimate: $E[^3\text{He}](\text{MeV}) \simeq 0.047 f_{TAE}(\text{kHz}) / n_{TAE} \approx 2 - 3 \text{ MeV}$
- Excitation of TAEs with lower mode numbers n_{TAE} correlates with an increase in 4.44 MeV gamma emission rate

Progress with the IFMIF Project EVEDA Phase

(Engineering Validation and Engineering Design Activity)



Сложности на пути от ИТЭР к термоядерной электростанции

- ИТЭР: < 2 смещений на атом (dpa) к концу программы
- Термоядерная электростанция: ~ 150 dpa (в течение 5 лет)
- Трансмутация железа → протоны и альфа-частицы
 $^{56}\text{Fe}(n, \alpha)^{43}\text{Cr}$ (пороговая энергия нейтронов 2.9 МэВ)
 $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ (пороговая энергия нейтронов 0.9 МэВ)

**→ Разбухание и охрупчивание материалов
в термоядерном реакторе**

Исследования и разработки в области радиационного материаловедения

Существующие источники нейтронов не могут дать ответы на все вопросы

1. Ядерные реакторы

- средняя энергия нейтронов ~ 2 МэВ
- генерация протонов и альфа-частиц не эффективна

2. Источники расщепления ядер (spallation sources) широкий спектр по энергии

- энергия нейтронов слишком велика

3. Установки для ионной имплантации (ion implantation facilities)

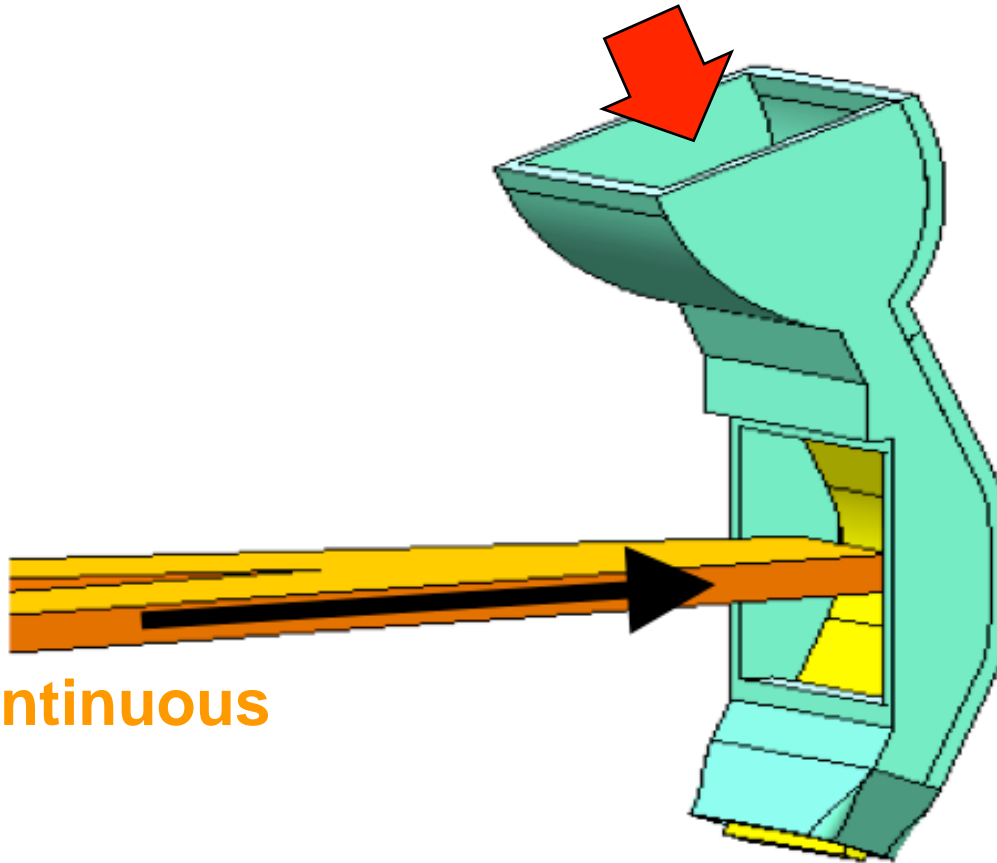
- малый объем и недостаточное смещение на атом (dpa)

Требуется создание специализированной установки (IFMIF)

IFMIF: принцип

Liquid Lithium
(15m/s, 25mm thickness, 250 °C)

40 MeV
D+ ions
10 MW continuous



Heat Flux
1 GW/m²

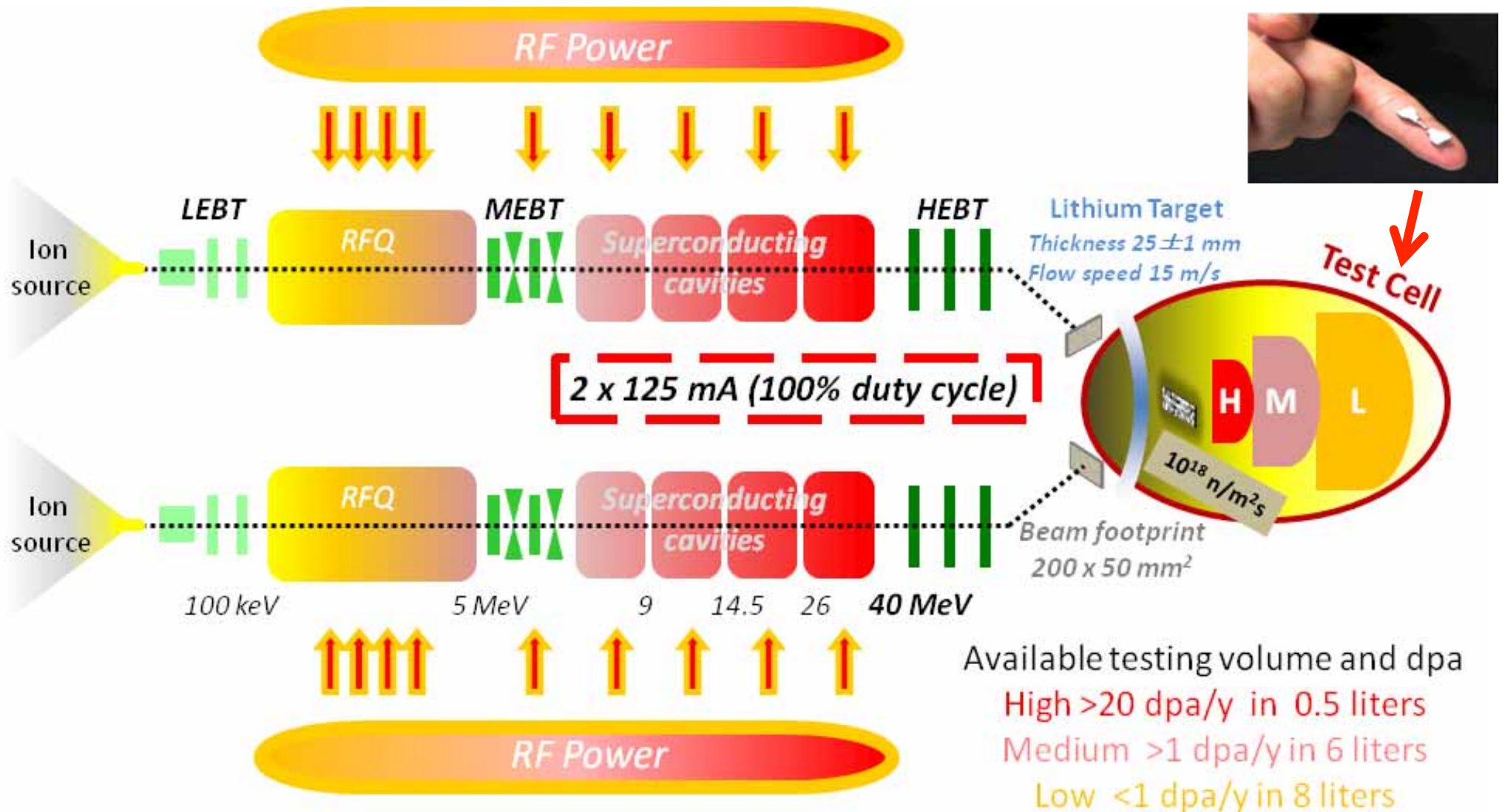
14 MeV Neutrons
Flux: 10¹⁸ s⁻¹m⁻²

IFMIF: сложная задача

- Accelerator driven source of neutrons
- Neutrons from $^{\text{nat}}\text{Li}(d,xn)$ reactions
 - $^7\text{Li}(d,n)^8\text{Be}$, $^6\text{Li}(d,n)^7\text{Be}$, $^7\text{Li}(d,n\alpha\alpha)$,
 $^7\text{Li}(d,np)^7\text{Li}$, $^7\text{Li}(d,nn)^7\text{Be}$, $^7\text{Li}(d,nd)^6\text{Li}, \dots$
- 2 accelerators 40MeV, 125mA, D⁺ ions → 2 x 5MW
- 10^{18} neutrons/m²/s with peak at 14 MeV
- Target heat load: 1GW/m² → liquid target needed
15m/s, 250 °C, total 10m³ of liquid Li
- Function of liquid Li target:
 - *generate sufficiently high neutron flux*
 - *dissipate 10 MW beam power*

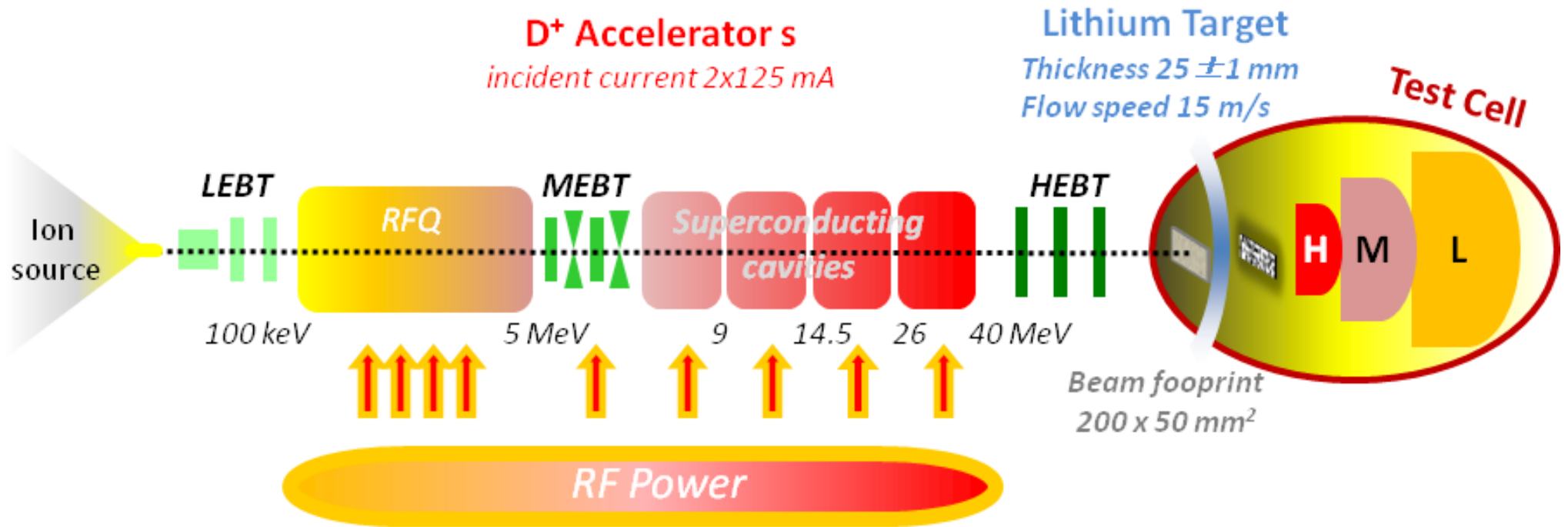
IFMIF: принцип

Original IFMIF : 2 accelerators of 40MeV deuterons



IFMIF: обзор

Prototype evaluations succesful during Broader Approach (EU-Japan)



Part 1
Prototype accelerator
In Rokkasho, Japan
Linear IFMIF Prototype Accelerator
(LiPac)

Part 2
Lithium target
tests in
Italy
Japan

Part 3
Test cell tests
In Japan
Germany
Belgium

LiPAC in Rokkasho (November 2016)

9 MeV – 125mA

IFMIF 原型加速器の入射系ビーム加速実験の成功と
高周波加速器 / 高周波源の据付開始を披露する記念式典
Celebration of the success of the injector commissioning
and the start of installation of the RFQ and RF power generator for Linear IFMIF Prototype Accelerator



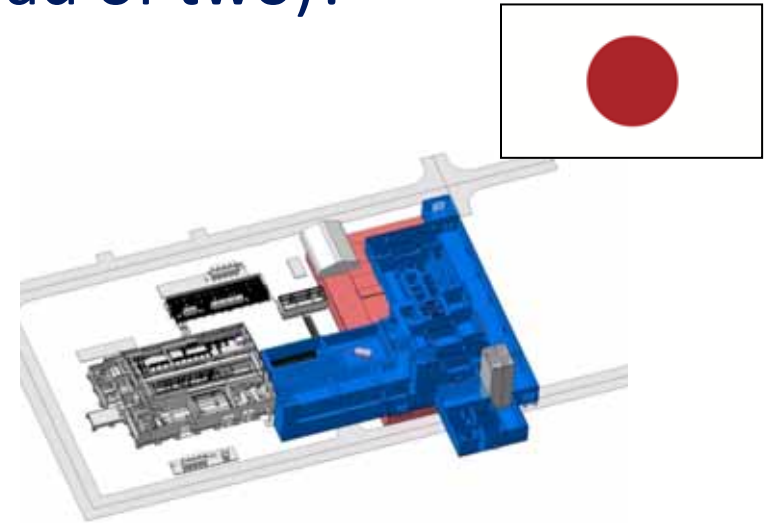
Do we need full version (2 accelerator) IFMIF ?

Ideas for a simplified version for quicker results for DEMO:

One only accelerator (instead of two)?



DONES in Europe



A-FNS in Japan

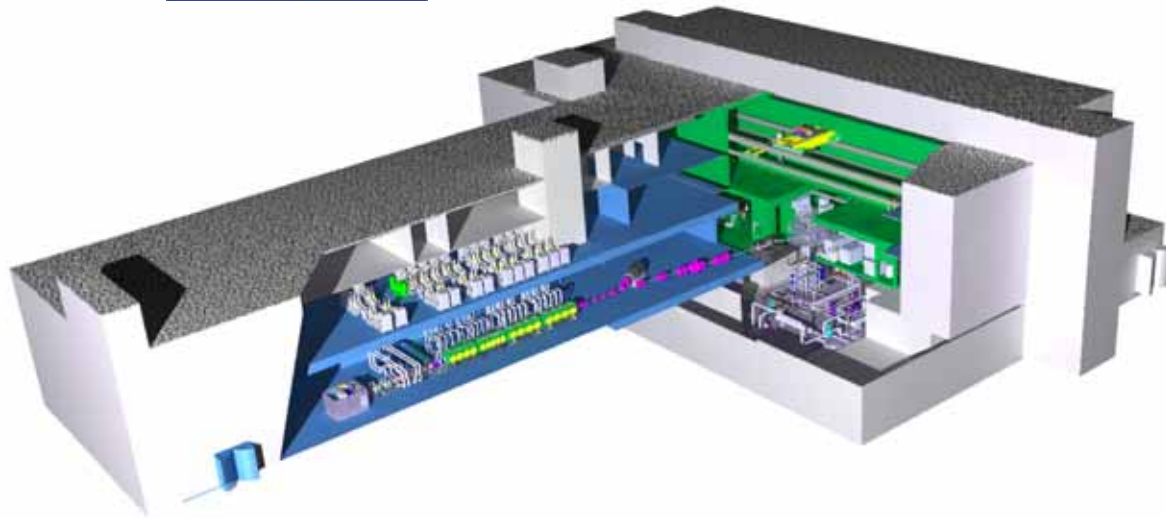
Candidates in EU for DONES:

Croatia, Poland, Spain, Belgium?

DONES = DEMO Oriented Neutron Energy Source

A-FNS = Advanced Fusion Neutron Source

Fusion Materials Irradiation Facilities



DONES
(DEMO Oriented Neutron Energy Source)

125 mA at 40 MeV

Now essentially waiting for a decision to construct DONES

Within 8 years from decision we could have 14 MeV neutrons

IBARRA, A., et al., *A stepped Approach from IFMIF/EVEDA toward IFMIF, Fus. Sci. Tech. Vol. 66 July/Aug 2014*

HEIDINGER, R. et al., *Technical analysis of an early fusion neutron source based on the enhancement of the IFMIF/EVEDA accelerator prototype, Fus. Eng. Des. 89 (2014) 2136–2140*

Заключение

Большие перспективы и поле для деятельности для молодых ученых

- JET (now) – работа с ИТЭР-подобной стенкой
- Wendelstein 7-X (now) – самый крупный стелларатор в мире
- ITER (2025?) – самый крупный токамак в мире
- T-15 and WEST – **(в ближайшее время) – в стадии сооружения**
- DONES (2024?) – исследования в области радиационного материаловедения

Спасибо за внимание !