DE LA RECHERCHE À L'INDUSTRIE

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PHYSICS AND TECHNOLOGY OF LOWER HYBRID CURRENT DRIVE (LHCD) IN TOKAMAKS

Tuong HOANG

Warm thanks to:
J. Achard, J.F. Artaud, Y.S. Bae, B. Beaumont, A. Bécoulet, J.H. Belo, J.M. Bernard, G. Berger-By, J.P.S. Bizarro, A. Cardinali, C. Castaldo, S. Ceccuzzi, R. Cesario, M.H. Cho, J. Decker, L. Delpech, B.J Ding, H. J. Do, R. Dumont, A. Ekedahl, J.Garcia, G. Giruzzi, M. Goniche, C. Gormezano, D. Guilhem, J. Hillairet, F.Imbeaux, J. Jacquinot, H. Jia, F. Kazarian, C.E. Kessel, S.H. Kim, H.J. Kim, J.G. Kwak, J.H.Jeong, X. Litaudon, R. Maggiora, R. Magne, L. Marfisi, S. Meschino, D. Milanesio, F. Mirizzi, P. Mollard, W.Namkung, L. Pajewski, L. Panaccione, S.I. Park, R. Parker, Y. Peysson, S. Poli, M. Prou, M. Preynas, A. Saille, G. Schettini, P.K. Sharma, M. Schneider, A. Tuccillo, O. Tudisco, G. Vecchi, R. Villari, K. Vulliez, H.L. Yang, B. Wan, Y. X. Wan.

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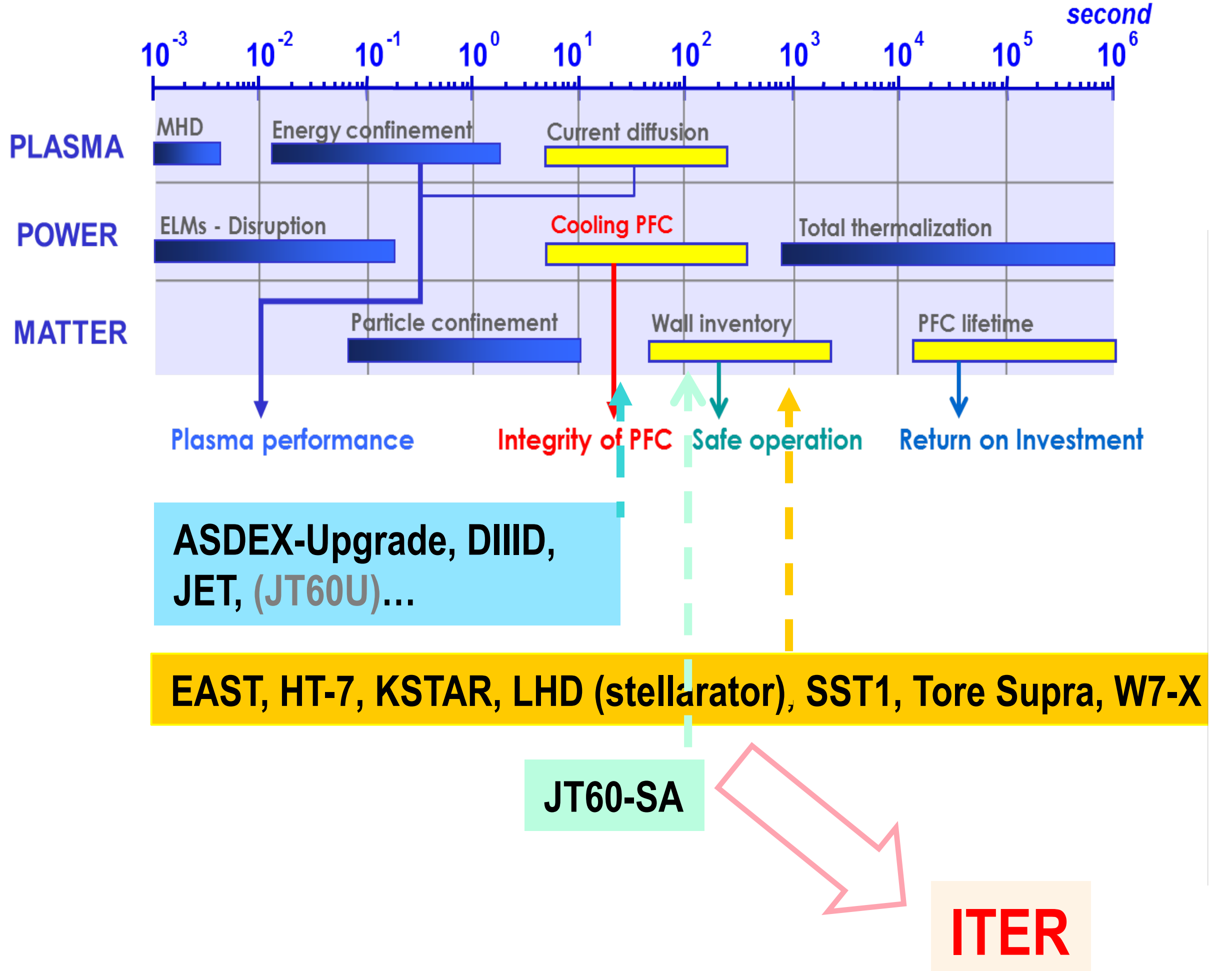
6th ITER International School, 2-6 Dec 2012

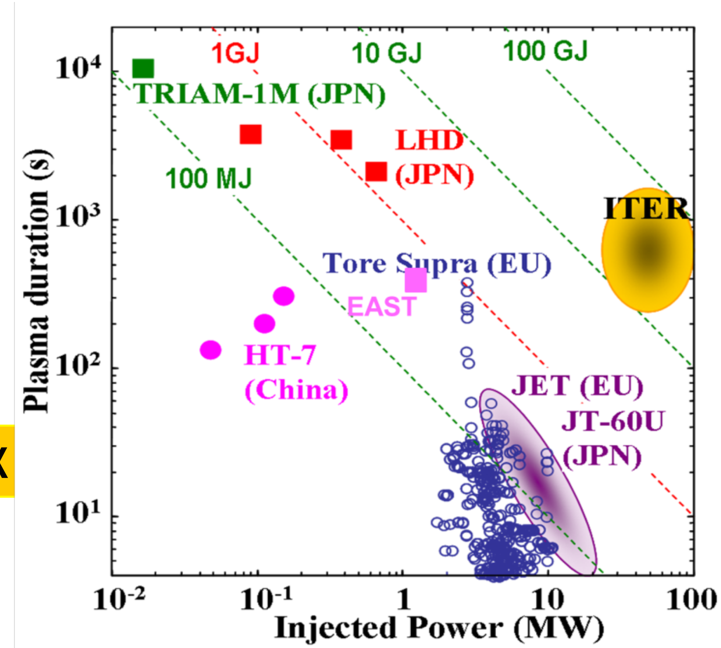
OUTLINE

- ❑ INTRODUCTION
- ❑ EXPERIMENTS
- ❑ ADVANCES IN TECHNOLOGY FOR CONTINUOUS WAVE (CW) OPERATION
  - ✓ R&D HIGH POWER KLYSTRONS
  - ✓ ACTIVELY COOLED ANTENNA
- ❑ LHCD FOR ITER
- ❑ CONCLUSIONS

MANY NATIONAL FUSION RESEARCH PROGRAMS CONCENTRATE NOW ON LONG PULSE DURATION OPERATION

- To address the integration of physics and technology, necessary for the design of reactor

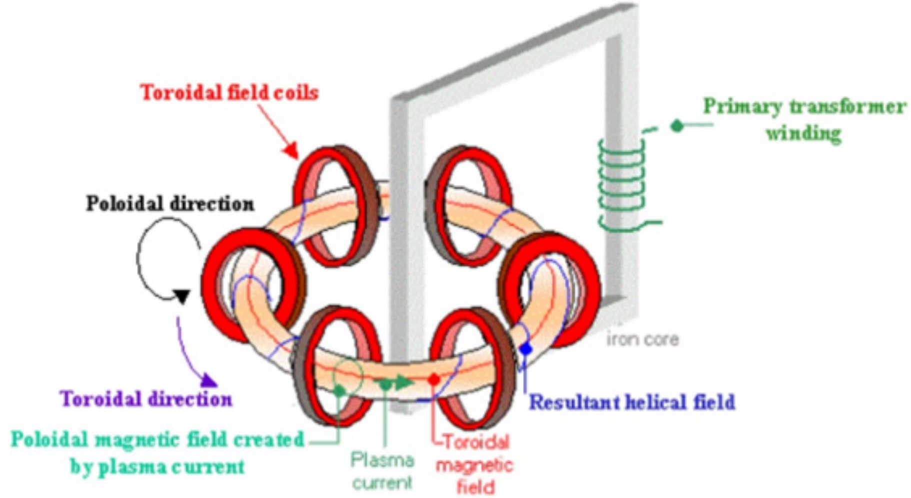




TOKAMAK MAGNETIC CONFIGURATION

- ❑ Extrinsically (intrinsically in stellarators) sustained by the combination of external magnets and currents circulating in the plasma
  - ✓ Inductive current driven by a toroidal electric field induced by a transformer
  - ✓ Bootstrap current generated by the plasma pressure gradient (mandatory for reactor operation) Bickerton, Nature 1971
- ❑ Inductive current is limited by the transformer capability. Bootstrap current limited by MHD instabilities.

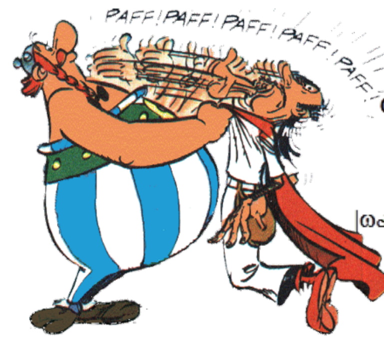
External non-inductive current drive, combining with superconducting magnets, is needed to sustain long duration plasmas
(Could reduce cost and complexity of fusion reactor)



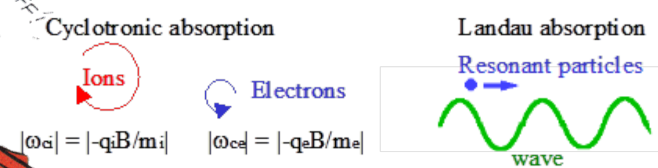
A schematic of a tokamak

Lecture by N. J.Fisch

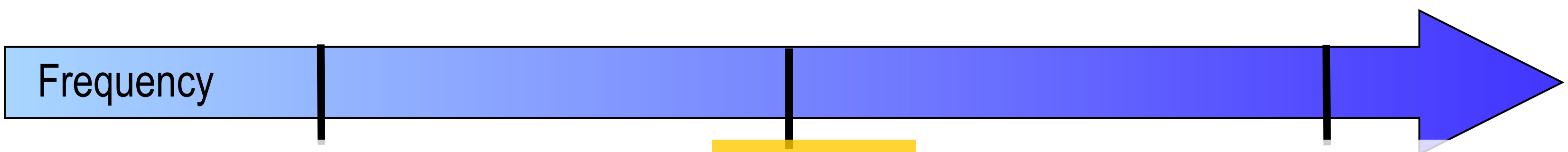
Neutral Beam injection
Collisions
Kinetic Energy transfer between particles



Radio-Frequency Waves
Cyclotron / Landau absorptions
Energy / Momentum transferred to particles



Ion Cyclotron Res. Frequency	Lower Hybrid Current Drive	Electron Cyclotron Res. Frequency
25~75 MHz	1~8 GHz	118~170 GHz
VHF	SHF	EHF
Radio and TV broadcasting	Mobile phones, microwave ovens	Terrestrial & satellite com, radio-astronomy



LHCD exhibits highest current drive efficiency in the present experiments

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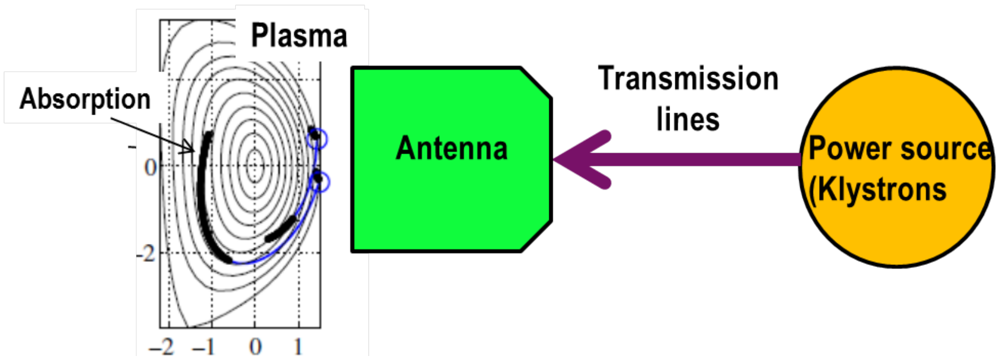
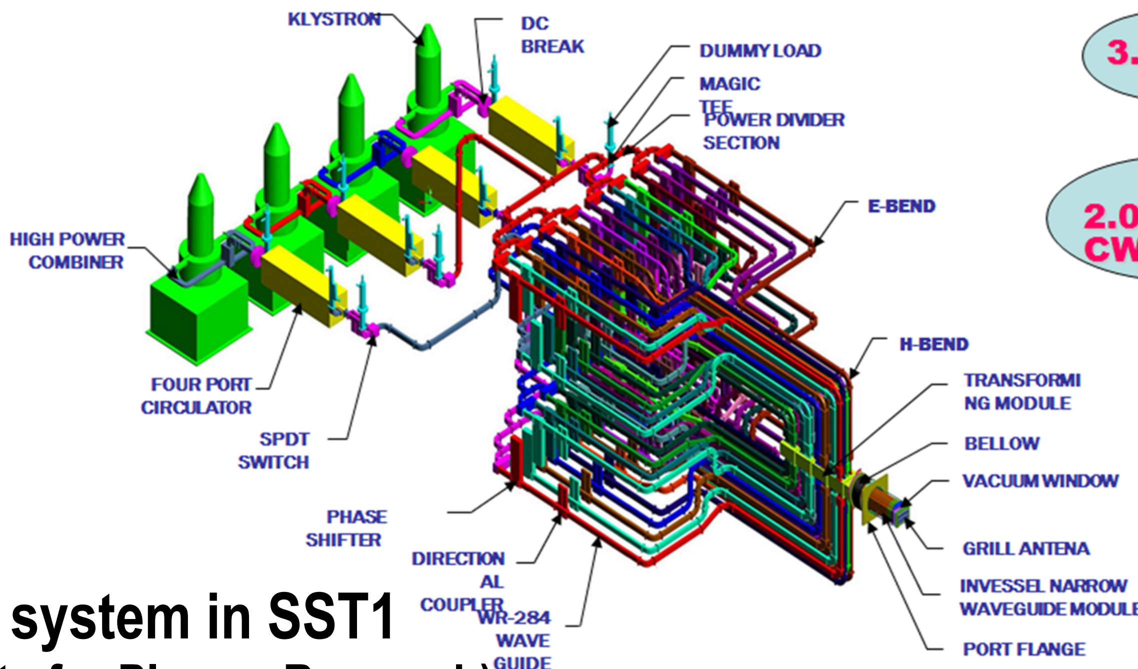
MAIN COMPONENTS OF LHCD SYSTEM

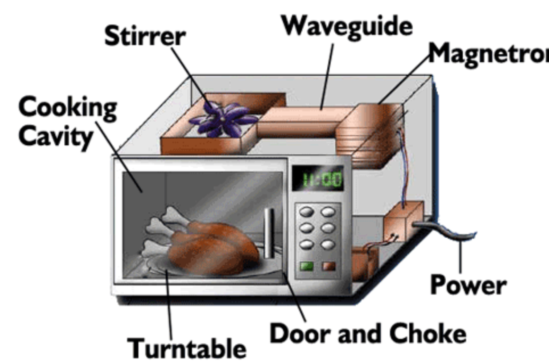




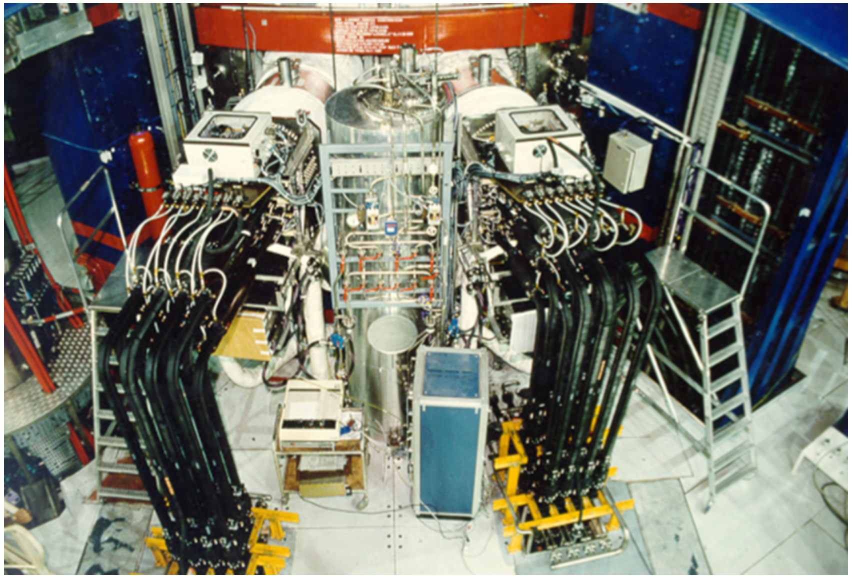
3.7GHz

2.0MW-CW

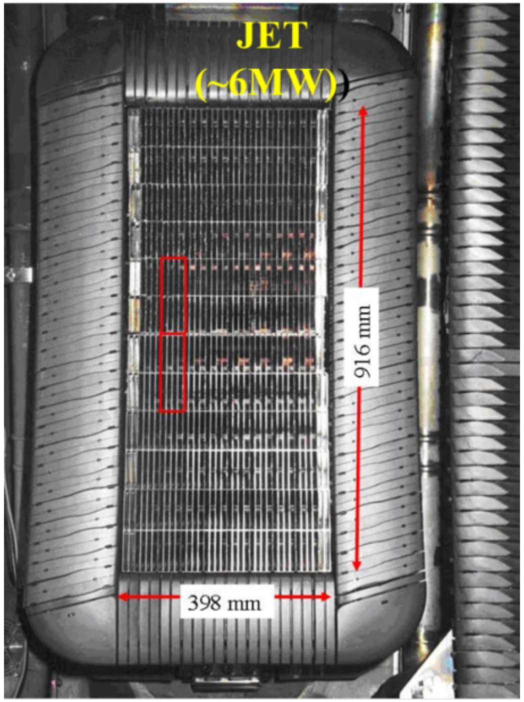
LHCD system in SST1
(Institute for Plasma Research)



...LARGE LHCD FACILITIES



Tore Supra LH Transmission Lines



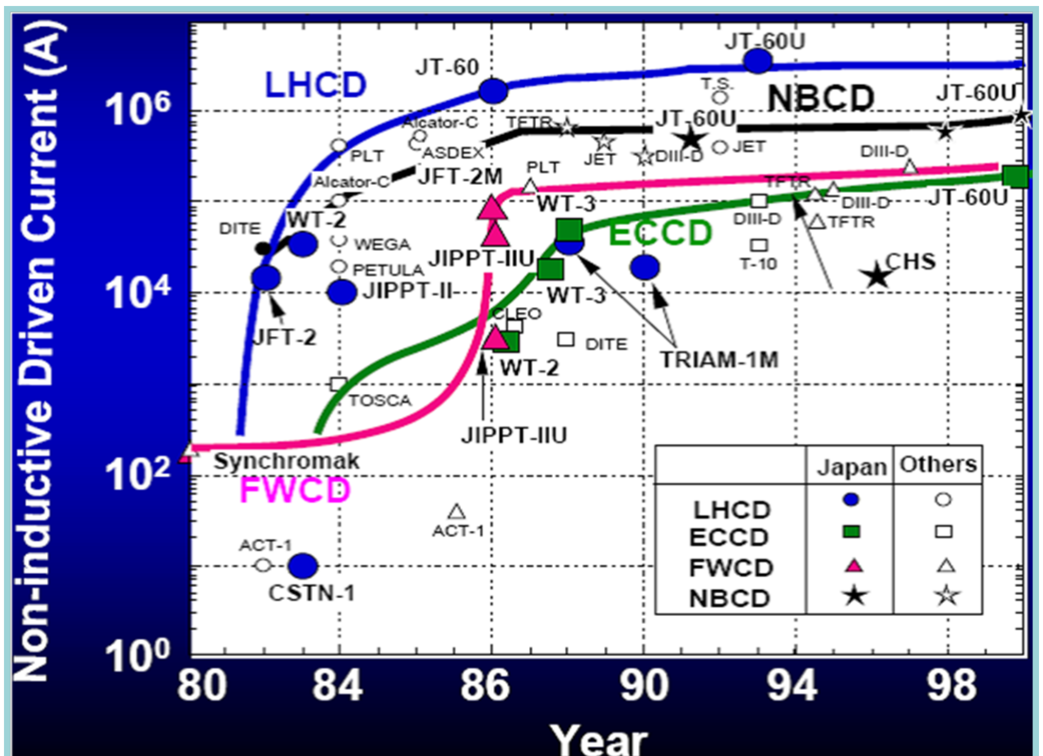
JET LH antenna

Tore Supra LHCD generator (16 klystrons)

LHCD IS EXTENSIVELY EXPLOITED IN A LARGE NUMBER OF FUSION DEVICES

- To save Volt-sec and/or to control plasma performance (confinement, MHD) via the plasma current density profile

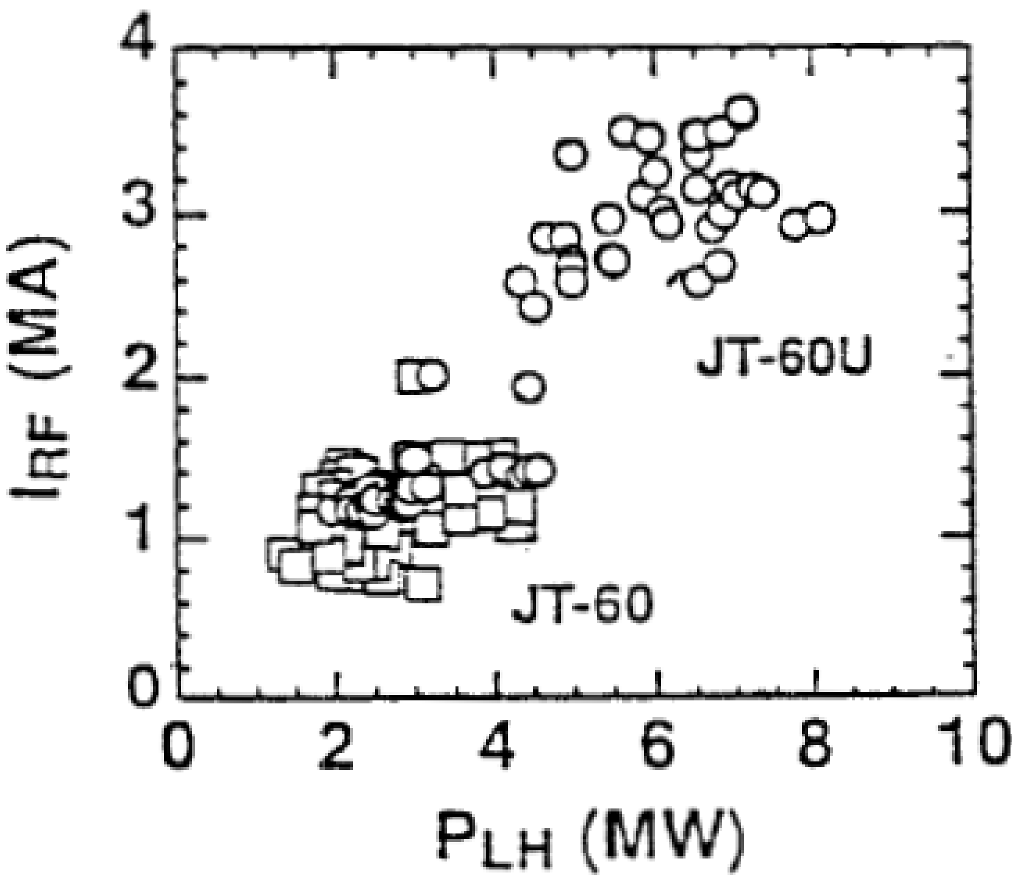
CHINA: EAST, HL-2A, HT-7; **US**: ALCATOR C-Mod (PBX-M, PLT); **EU**: COMPASS, FTU, JET, Tore Supra, (ASDEX, FT, Petula, WEGA-Grenoble); **Japan**: JFT-2, JIPPT-II, JT-60U, QUEST, TRIAM, WT-2. **India**: SST1. **Korea**: KSTAR



[Courtesy Ushigusa]

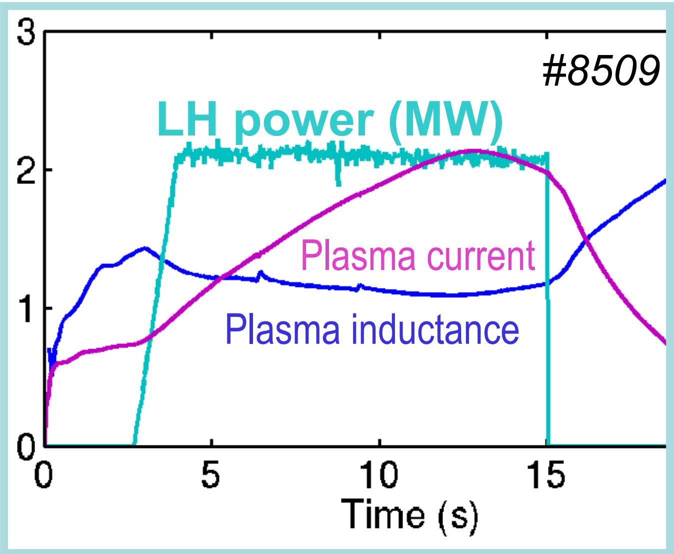
LOWER HYBRID WAVES DRIVE MEGA-AMPERE CURRENTS

- ❑ Up to 3.6 MA in JT60
- ❑ 2MA in Tore Supra LH-assisted current ramp-up experiments



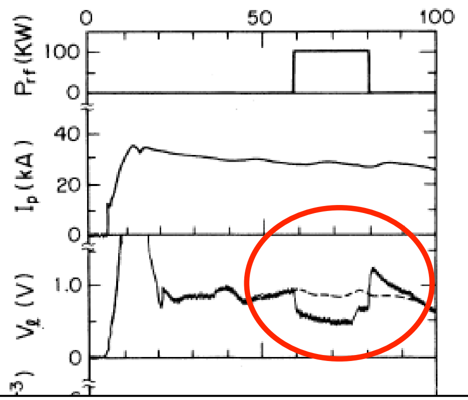
H. Ninomiya, 15th IEEE/NPS Symposium Fusion Engineering

Tore Supra



Hoang, 19th EPS 92

PULSE DURATION FROM MILLISECONDS REACHED HOURS



1st Exp. Observation in JFT-2 (1980)
LH current 15kA for <100ms
Plasma current 30kA
LH power 125kW
Elec. temperature ~0.25keV

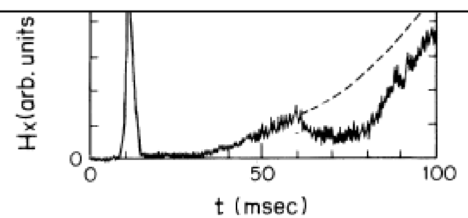
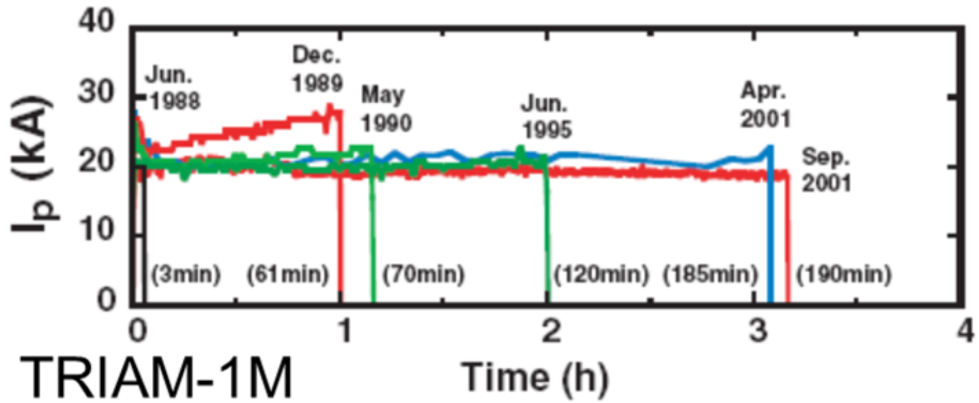


FIG. 1. Typical plasma shot: B_t = 14 kG and $\Delta\varphi$ = 90°; the solid lines show the shot with the rf pulse and the dotted lines with no rf pulse.

T. Yamamoto, Phys Rev Lett 1980

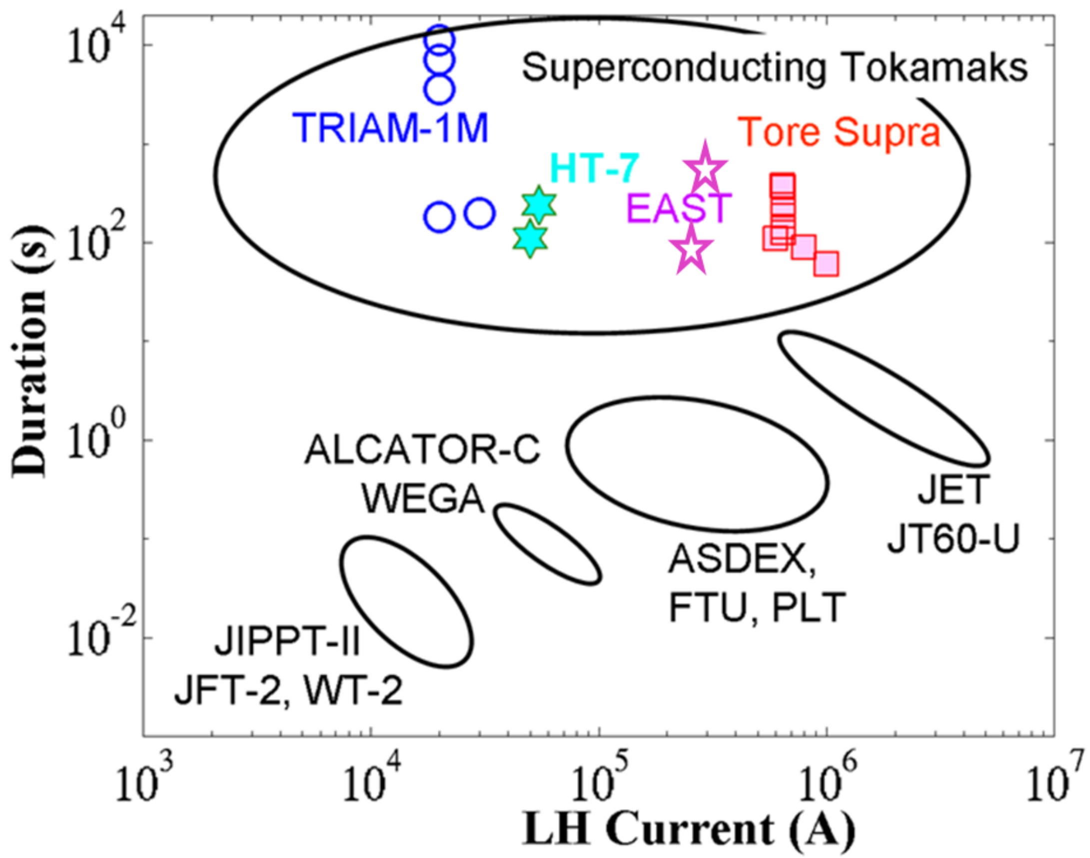
Pulse **3h10**' achieved inTRIAM-1M
Plasma density 1×10^{18} m^{-3}
LH power <10 kW
(R = 0.8m, a × b = 0.12m × 0.18m and B = 8T)



H. Zushi , Nucl Fusion 2003

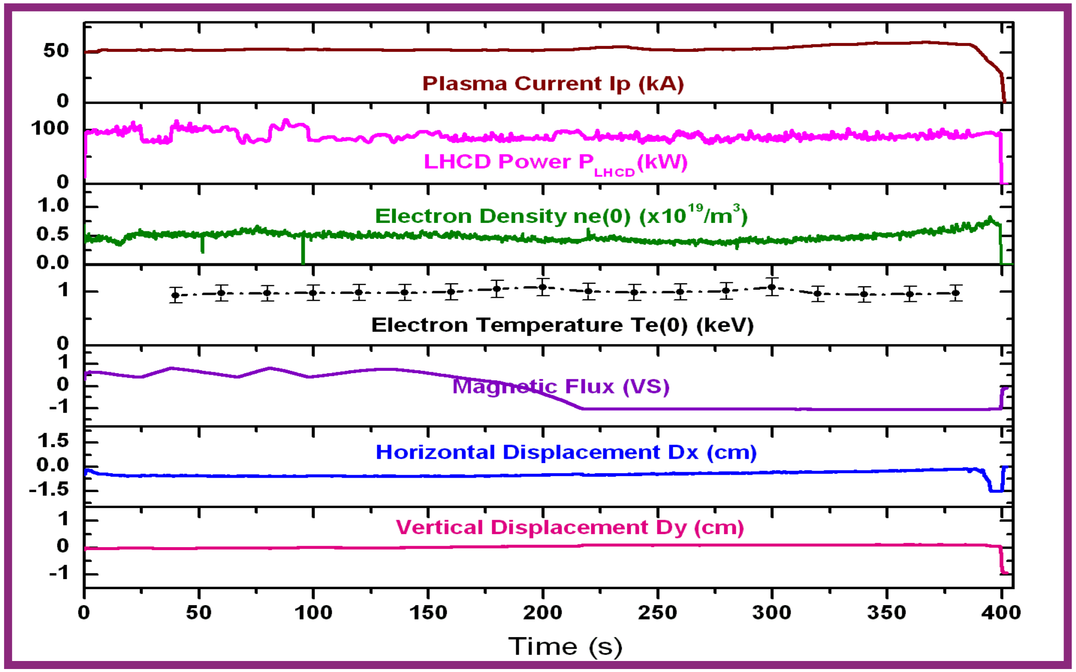
LHCD CW CAPABILITY IS USED OR PLANNED IN ALL SUPERCONDUCTING TOKAMAKS

- To sustain long pulses in combination with superconducting magnets
- Experiments started in KSTAR. Planned in SST1.



HT-7 PLASMA SUSTAINED BY LHCD FOR 400S

Plasma current **50kA**
LH power **100 kW**
Elec. temperature ~1keV

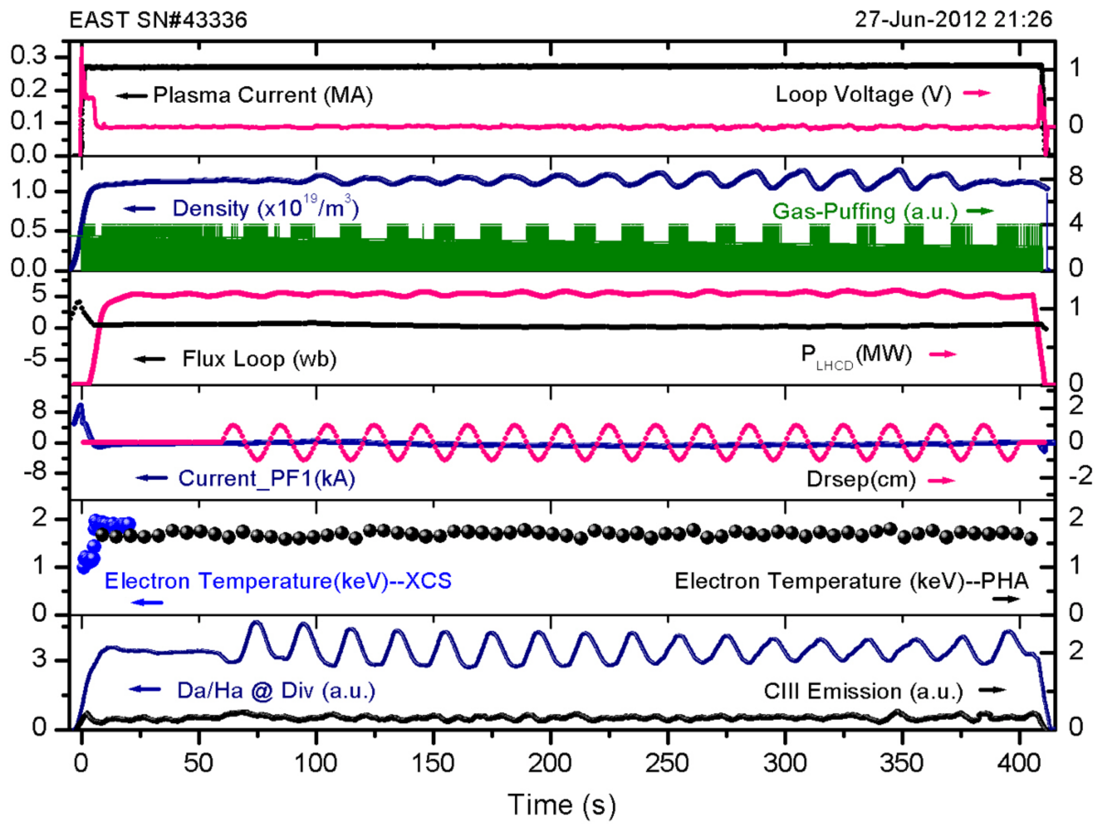


B. Wan, Nucl Fusion 2009

MOST RECENT LONG PULSE DIVERTOR DISCHARGE IN EAST

Discharge lasting more than 400s realized in July 2012, in combining

- ✓ Real-time control to maintain plasma shape, power coupling
- ✓ Strike point sweeping and varying plasma configuration for mitigating divertor heat load



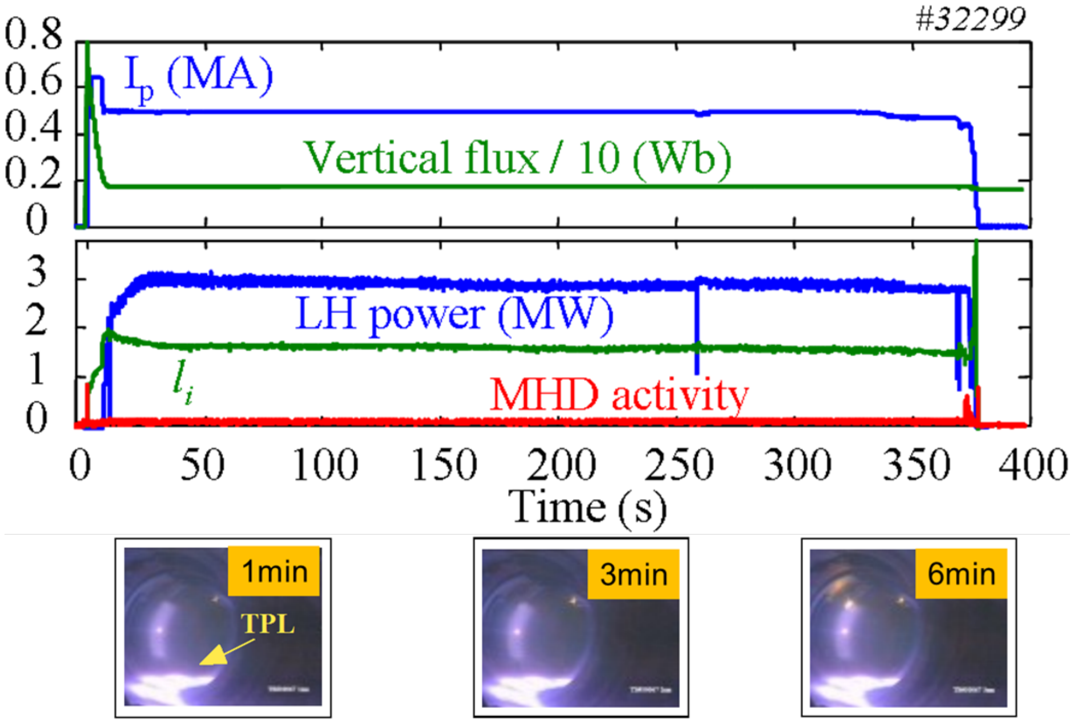
Plasma current **0.27MA**

LH power **1.2 MW**

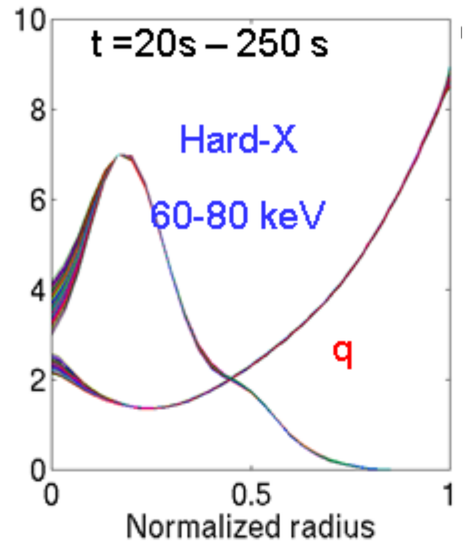
Elec. temperature ~2keV

PLASMA SUSTAINED BY LHCD OVER 6'30" IN TORE SUPRA

Actively cooled plasma facing components allowed injecting / extracting energy of **1.07 GJ**



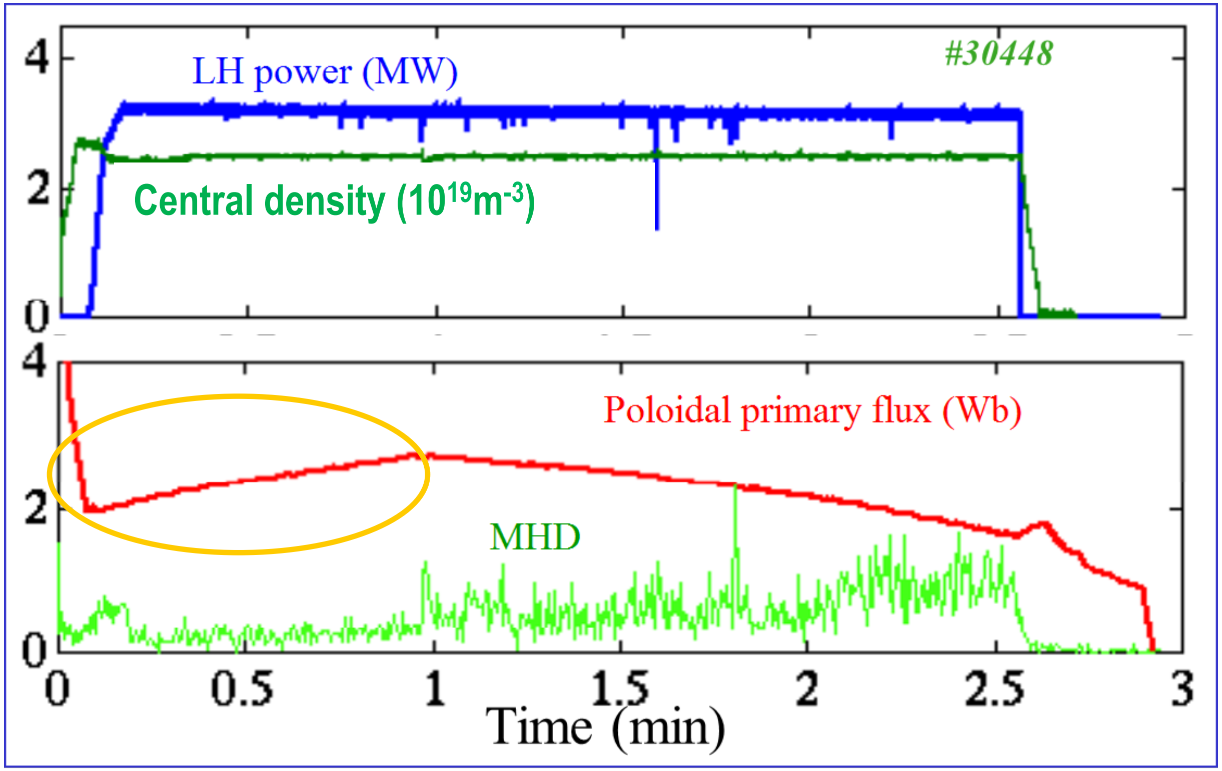
Plasma current **0.5 MA**
LH power **~3MW**
Elec. temperature ~4.7keV



D. Van Houtte, Nucl Fusion 2004

PRIMARY TRANSFORMER RECHARGE IN TORE SUPRA

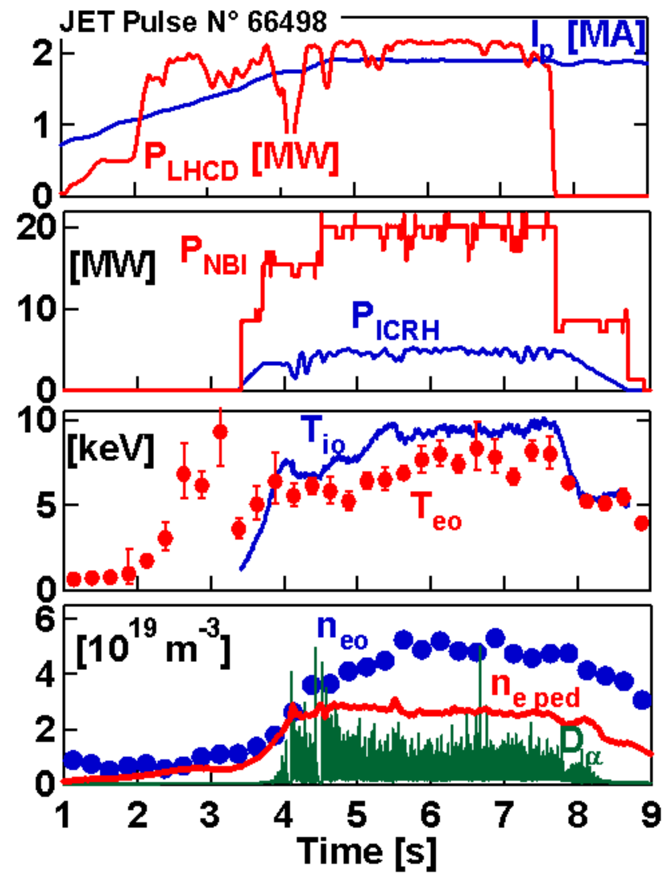
- Over Current Drive during 1 minute
- Limited by MHD which induce fast electrons deconfinement -> CD efficiency drops



[Jacquinot, 2003]

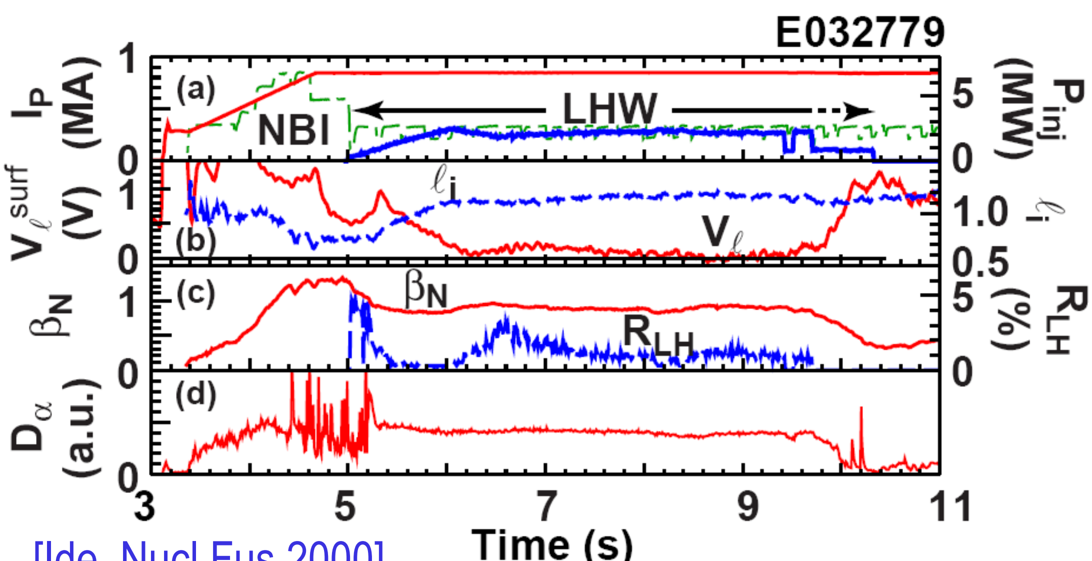
LHCD USED FOR REALIZING OR SUSTAINING HIGH PERFORMANCE PLASMAS

- ITER relevant high triangularity plasma achieved at JET (T_i~T_e)
  - ✓ LHCD used to trigger localcalized reduction of transport (Internal Transport Barrier, ITB) by preforming the current density profile
    -> good electron confinement



[Litaudon, PPCF 07]

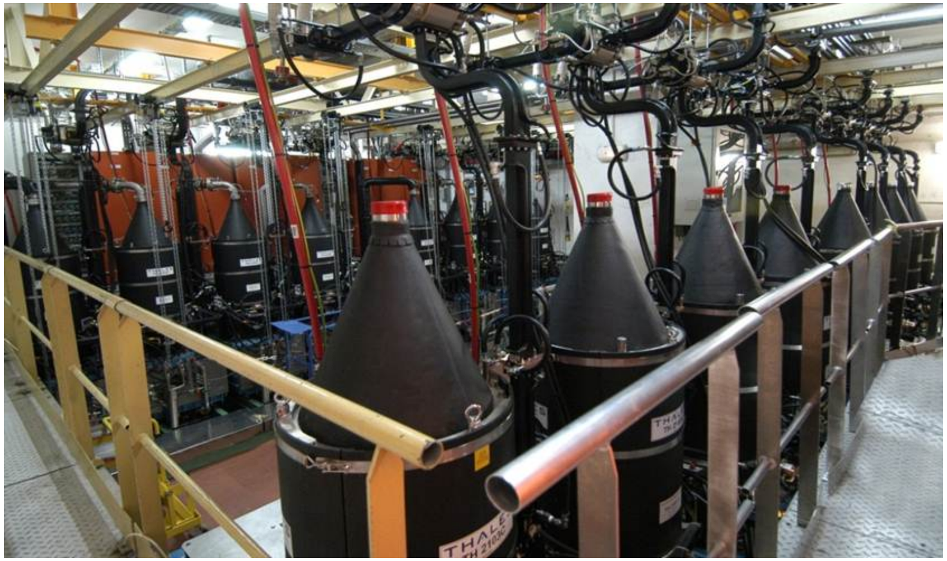
- Quasi-steady state ITB sustained in JT60-U

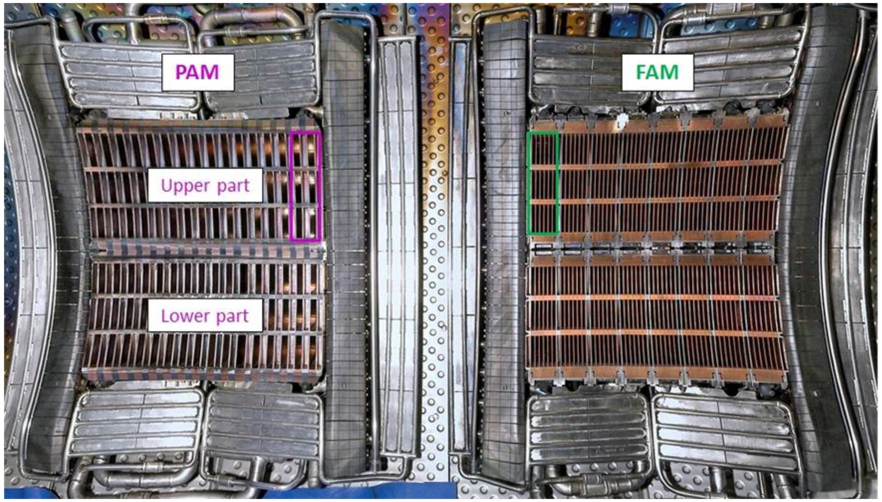


[Ide, Nucl Fus 2000]

Capability **~10MW / 1000s** at the generator

- 16 CW klystrons at 3.7GHz
- Two launchers: Passive Active Multi-junction (PAM) and one Full Active Multi-junction (FAM)

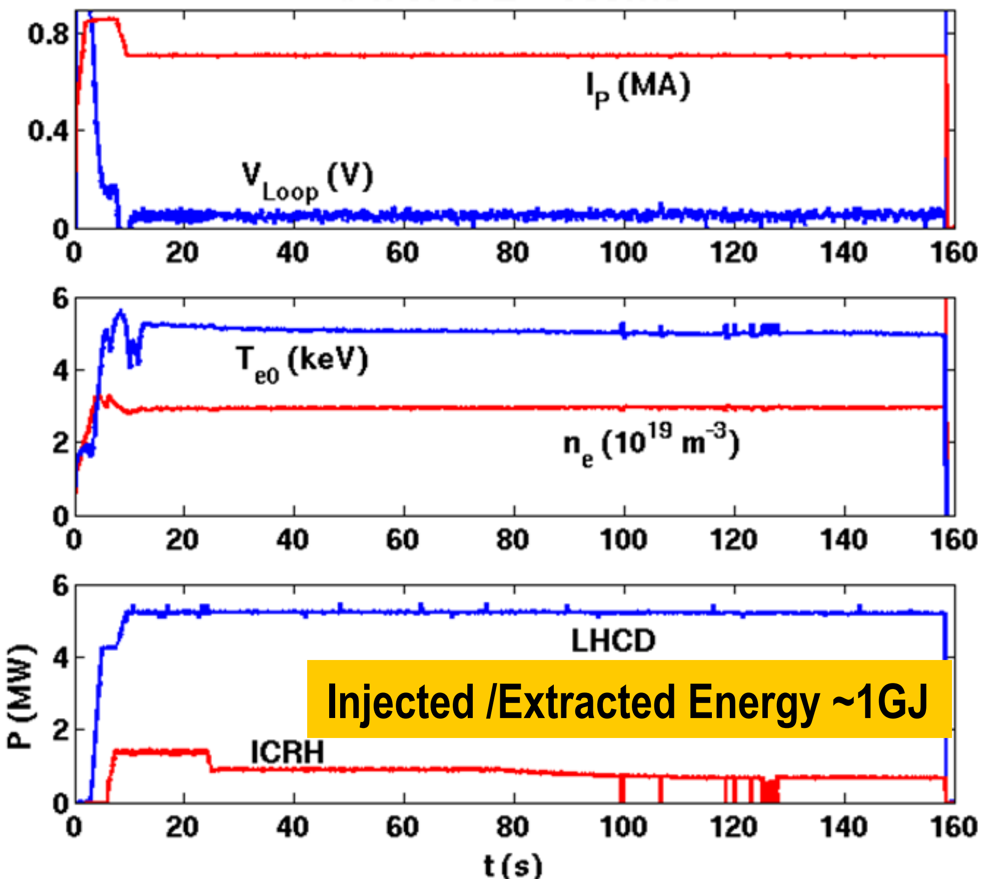




0.8 GJ OF LHCD INJECTED INTO TORE SUPRA PLASMA

- 5.3 MW of LHCD combined with ~1MW of ICRH during 160s
- Non-inductive current fraction 80%

#47979

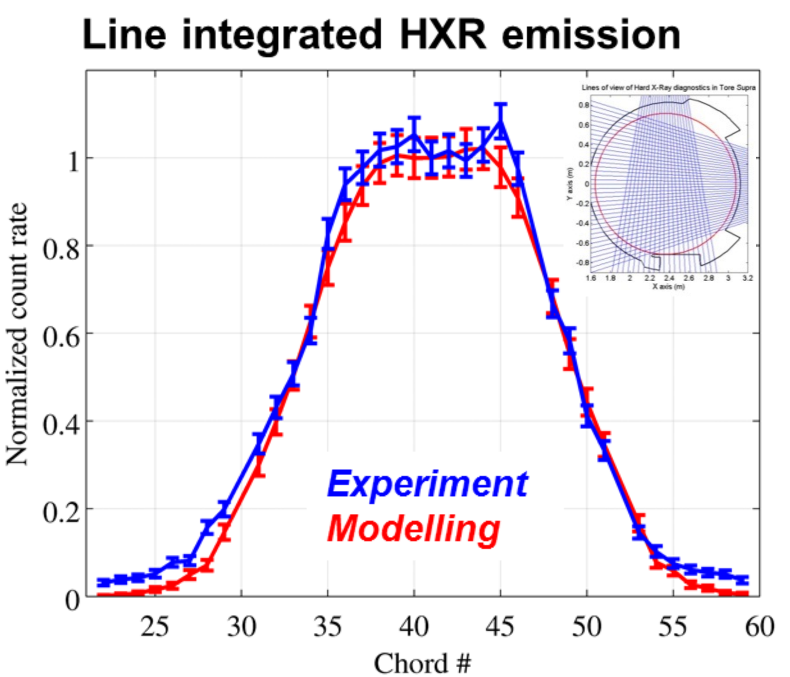


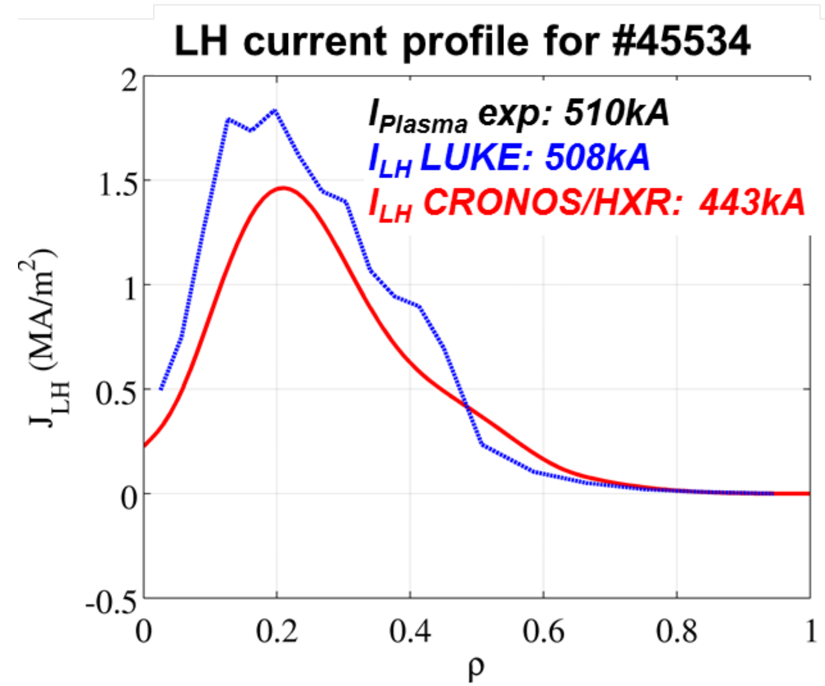
Dumont, EPS 2012

MODELING IS CAPABLE OF REPRODUCING EXPERIMENTS

Peysson, L4
This IIS

- Package of codes C3PO (ray-tracing), LUKE (Fokker-Planck), R5X2 (Bremsstrahlung) reproduces pretty well the Hard-X measurements and the LH current
- But still need robust models, as well as good diagnostics



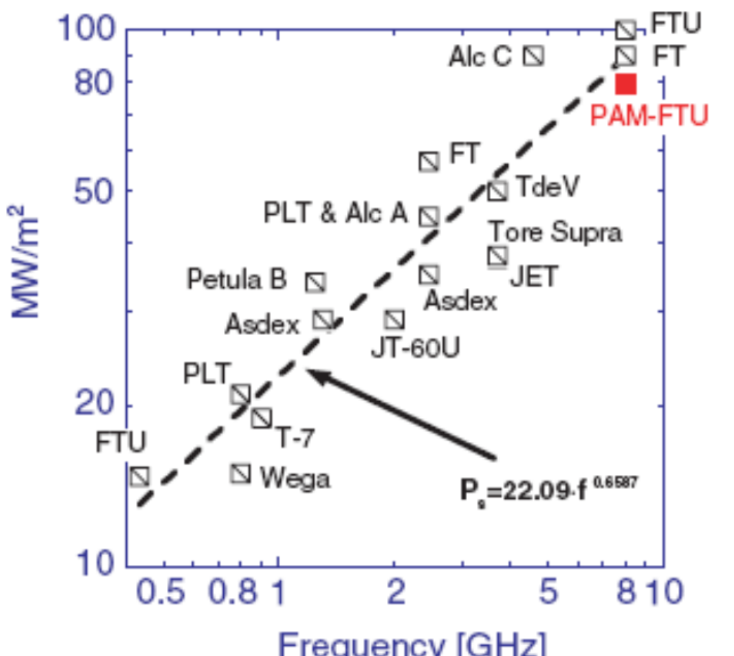


Y Peysson and J Decker, PoP 2008
Peysson PPCF 2011
Ekedahl, 19th Top Confon RF Power in Plasmas
Decker ,19th Top Confon RF Power in Plasmas

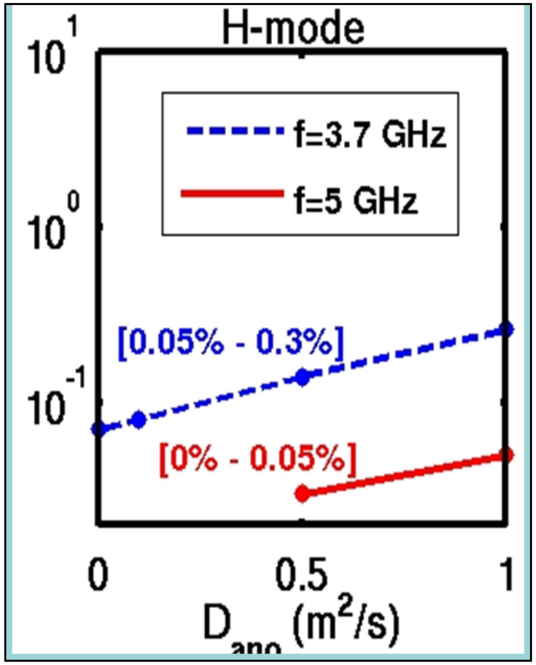
SOURCE FREQUENCY MUST BE HIGH ENOUGH

- To maximize the power handling capability of the antenna
- To avoid the parasitic absorption by fusion generated alpha-particles in reactor-grade devices
- Choice of the frequency is constrained by the feasibility of manufacturing the antenna. Size of the waveguide decreases with increasing the frequency source. 3-5 GHz is a reasonable range

Power density of antenna increases with frequency



Pericoli, Nucl Fusion 2005



Fraction of LH power absorbed by alpha particles in ITER baseline scenario versus alpha diffusivity

Schneider, Nucl Fus 2006

CW KLYSTRONS ALREADY USED OR BEING INSTALLED IN EXISTING TOKAMAKS

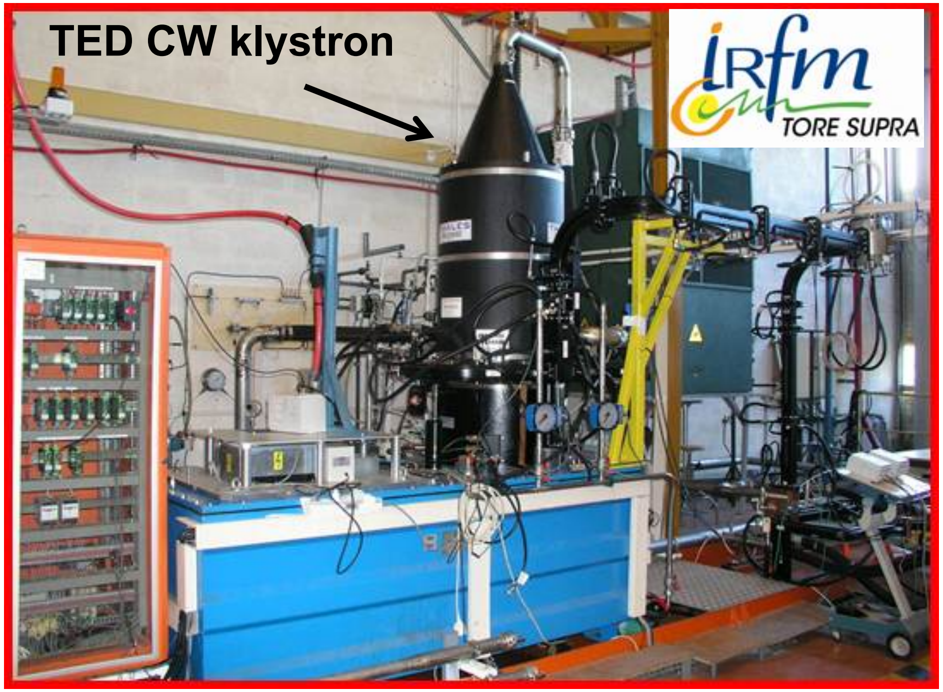
- ❑ One klys of 500kW / 5GHz produced by Toshiba. Operation on KSTAR started
- ❑ 250kW / 4.6GHz klys. produced in series by CPI (Communications and Power Industries, Inc), will be in operation on EAST
- ❑ 700kW / 3.7GHz produced in series by Thales Electron Devices in operation on Tore Supra

Frequency (GHz)	Design target	Achieved performance
5 (TETD-E3762RD0)	500kW/CW	**300kW/800s (VSWR=1.12)** (Factory test: 300kW/12min.) 450kW/20s (VSWR=1.2) 500kW/2s (VSWR=1.2)
4.6 (CPI)	250kW/CW	**259kW/CW** (*)
3.7 (TED-TH2103C)	700kW/CW	**767kW/CW (VSWR=1)** **670kW/CW (VSWR=1.4)**

(*) Lenci, Vacc. Electronics Conf. IVEC 2009, IEEE International

Kazarian, Fus Eng Design 2009
Park, Fus Eng Design 2010
Do, Fus Eng Design 2011

Necessary for prior klystron commissioning and the validation of high power CW transmission line components to minimize risks for the LHCD operation



Test stand for 3.7 GHz klystrons at CEA-IRFM

Test stand for 5 GHz klystrons at NFRI

Delpech, Fus Eng Design 2011
Do, Fus Eng Design 2011
Park Fus Sci Tech 2012

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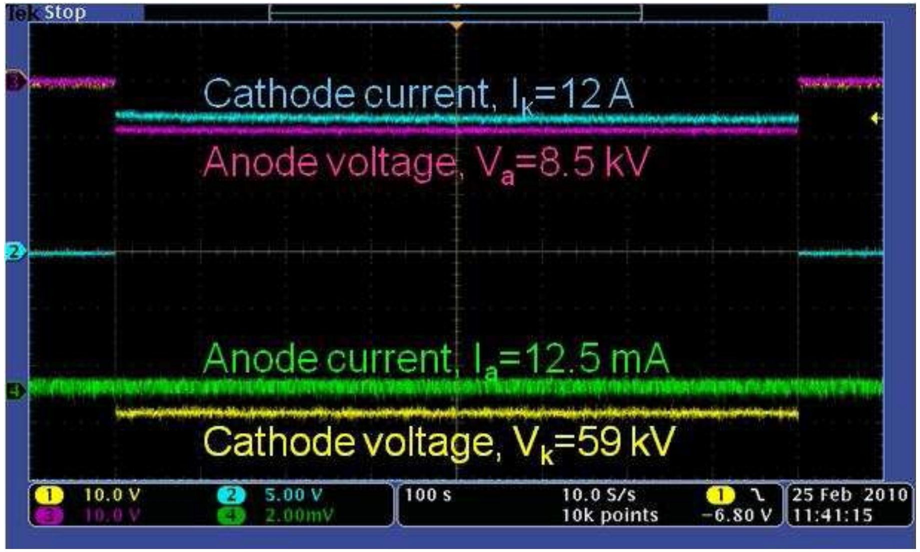
5GHZ CW KLYSTRON PROTOTYPE COMMISSIONED ON THE NFRI TEST BED

- Efficiency of ~ 45% @ 300 kW /CW, on matched load (~ 50% @ 500kW/0.5s)
- Commissioned on KSTAR plasmas started (Initial 500 kW LHCD system)

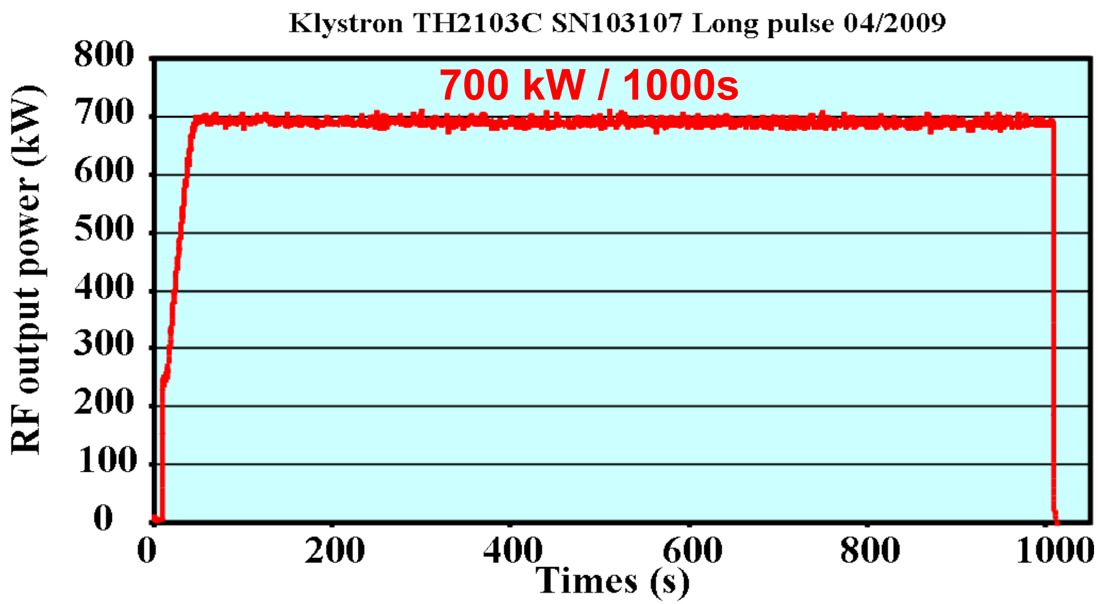


*Oscilloscope screen shot of the cathode (beam) and the anode voltages and current for **304 kW / 800s pulse***

Do Fus. Eng. and Design 2011

EIGHTEEN 3.7GHZ / CW KLYSTRONS PRODUCED FOR TORE SUPRA

- ❑ Each klystron qualified at 720kW/CW on matched load (VSWR =1) provided routinely ~ 620kW / CW in relevant plasma conditions (VSWR =1.4)
- ❑ Efficiency ~ 47%

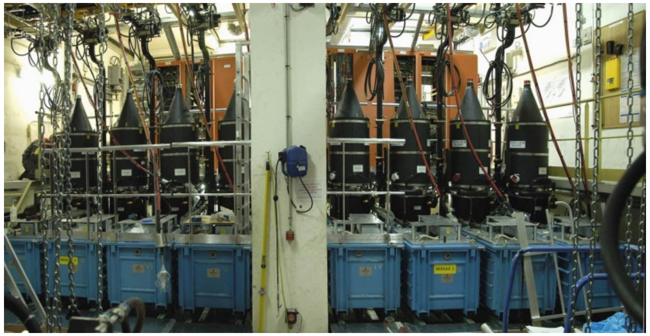


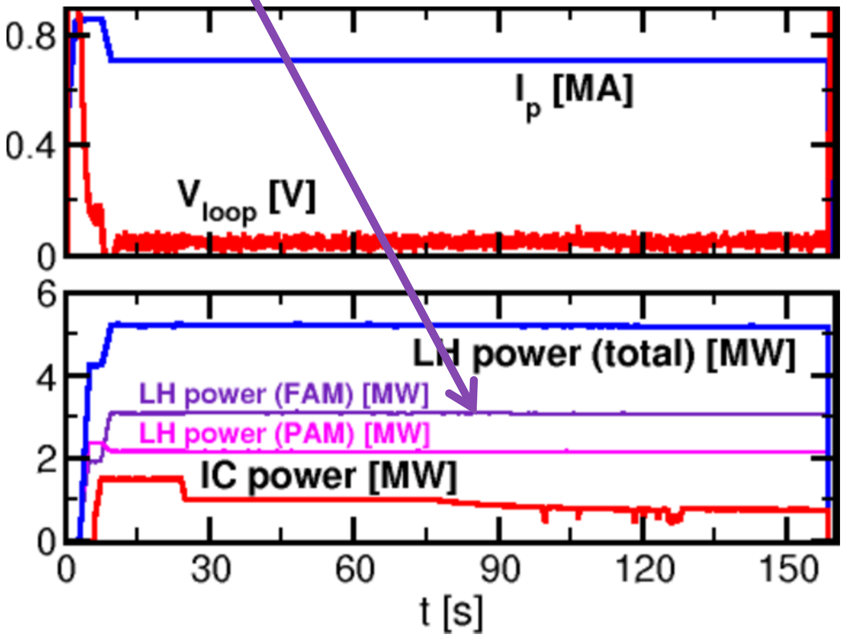
Kazarian et al., Fus Eng Design 2009

Delpech, 18th Top Conf on RF Power in Plasmas 2009

FIRST SET OF EIGHT CW KLYSTRONS 3.7GHZ QUALIFIED ON TORE SUPRA PLASMAS

- ❑ Delivered powers more than 4MW over 5s
- ❑ 520kW - 620kW per klystron routinely (80% - 100% of capability)
- ❑ Pulse 3MW / 160s achieved





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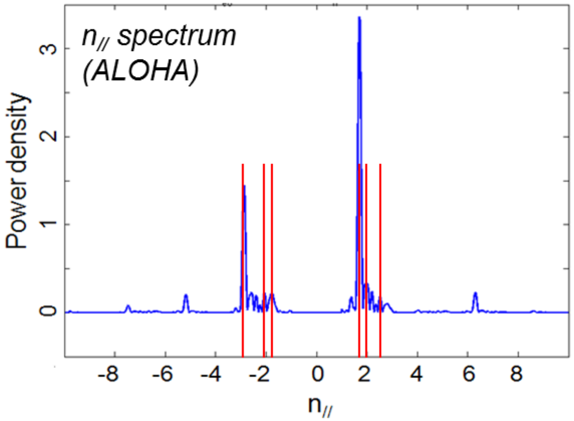
ANTENNA MUST BE ROBUST ABLE TO OPERATE IN ANY PLASMA CONDITION

A trade-off between many considerations:

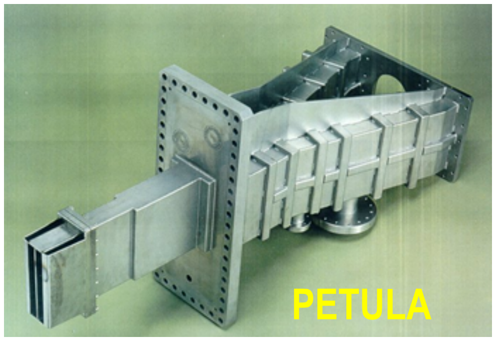
- Current drive efficiency (flexible choice of parallel index of the wave $N_{//}$ -> antenna geometry)
- Power coupling capability (deal with plasma density perturbations (ELMs), coupling at long distance plasma-antenna)
- Power handling capability (power density)
- Heat load removal capability (active cooling)
- Neutron shielding (ITER case)
- Mechanical structure (resistant front to withstand disruptions)
- Fabrication feasibility

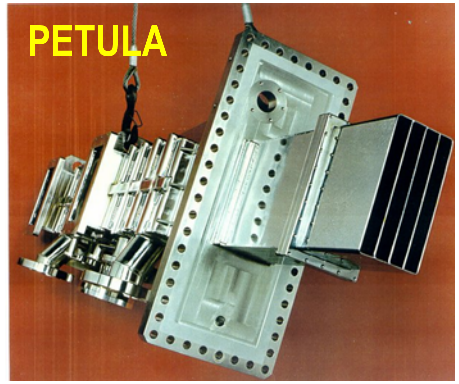
'experimental' power spectrum of a Tore Supra LHCD laucher



SOME GENERATIONS OF ANTENNA

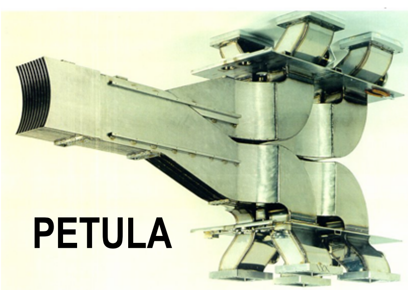
2 waveguides

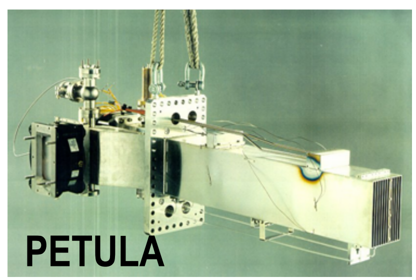




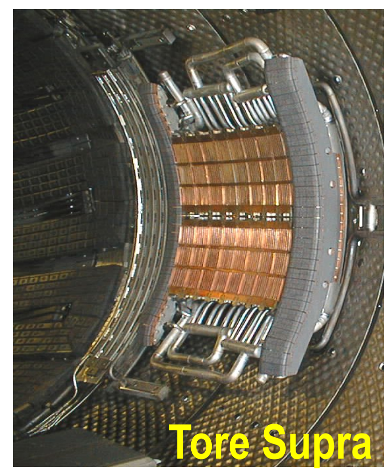
4 waveguides

8 waveguides





12 wg multijunction



Actively cooled 284 wg multijunction

More and more complexe….> 1000 waveguides in ITER!

TORE SUPRA PASSIVE ACTIVE MULTIJUNCTION (PAM) ANTENNA

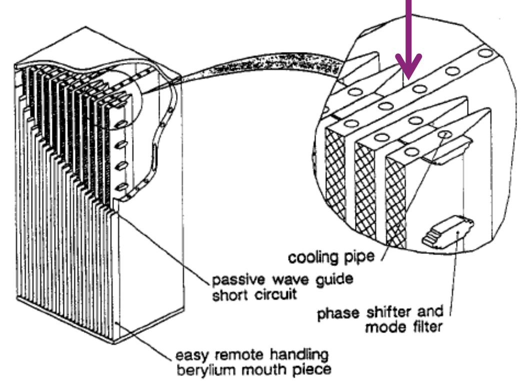
- ❑ 96 active waveguides (76×14.65mm) alternately with 102 passive ones
- ❑ Actively cooled by hot pressurized demineralized water (30 bars at 150 ◦C)

Passives waveguide allow mechanical strength to withstand disruptions and enables to put water cooling pipes close to the antenna front face

Passive wg

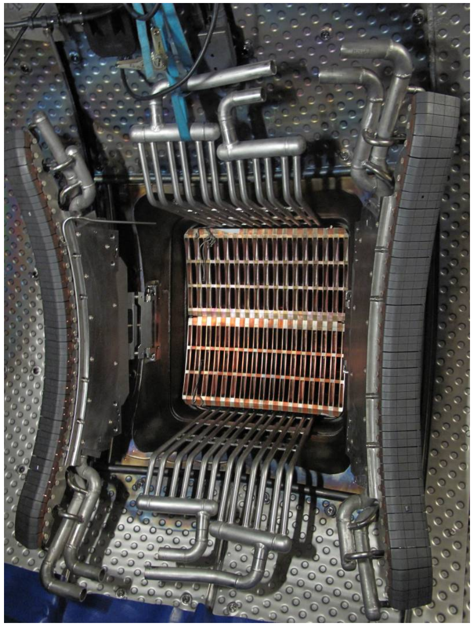
Active wg

Cooling pipe



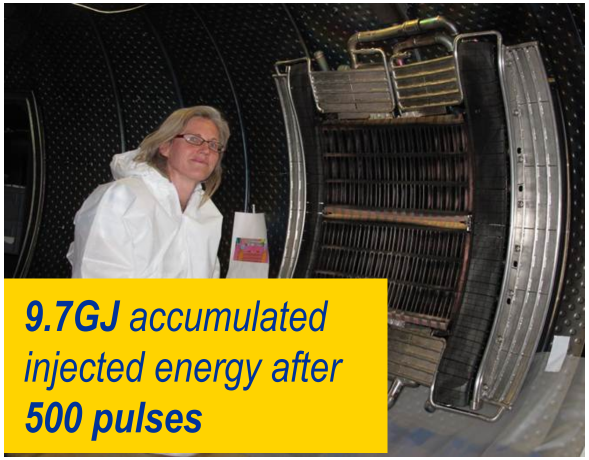
Bibet, Nucl Fusion1995
Guilhem Fus Eng Design 2111

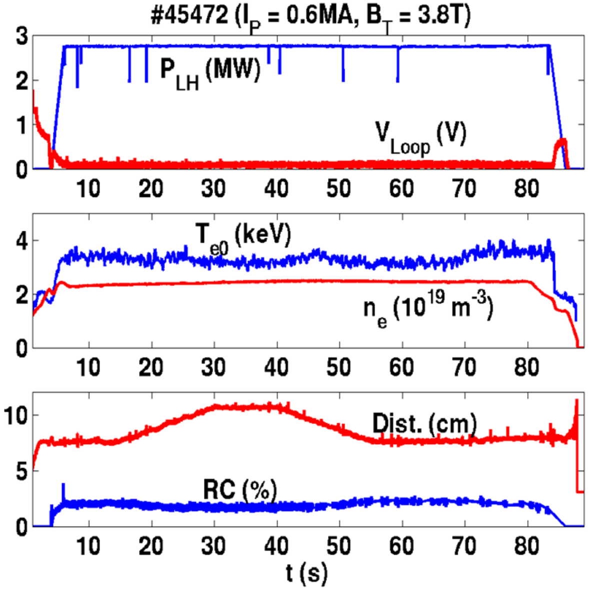
INSTALLATION OF THE TORE SUPRA PAM

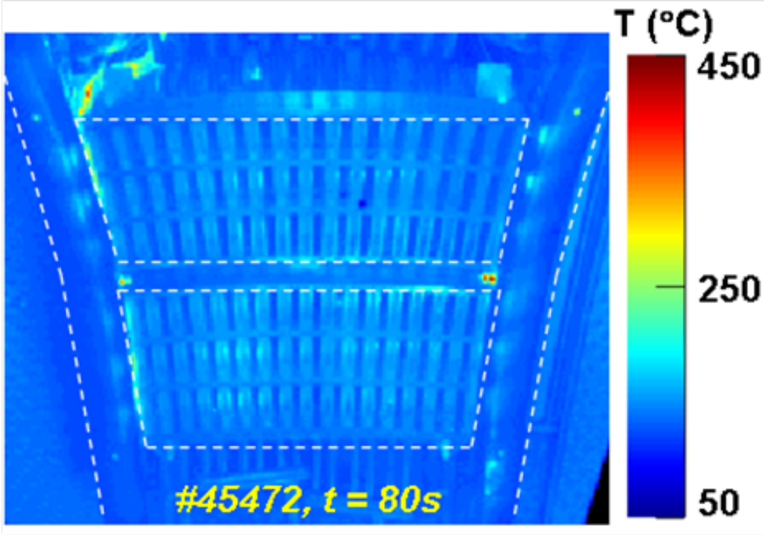


PAM VALIDATED ON TORE SUPRA PLASMAS

- ❑ Fast commissioning: 2.7MW reached after 240 pulses on plasma
- ❑ ITER relevant power density 25MW/m^2 for 78 seconds
- ❑ Very low reflected power ~2% at large plasma-launcher gap ~ 10 cm
- ❑ Efficient cooling: waveguides and side protections remain below 300°C



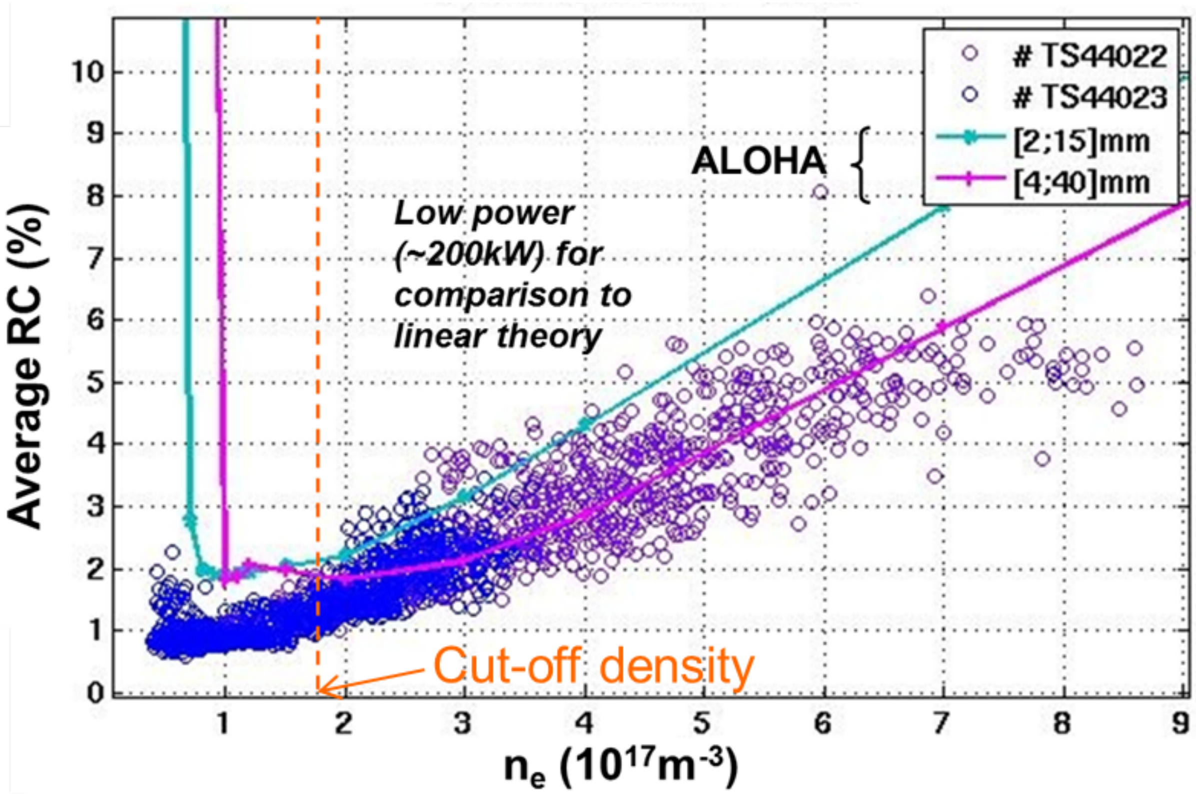




COUPLING AGREES WITH LINEAR THEORY

- In agreement with the design specification and linear theory of wave coupling

  Good confidence for ITER LHCD design

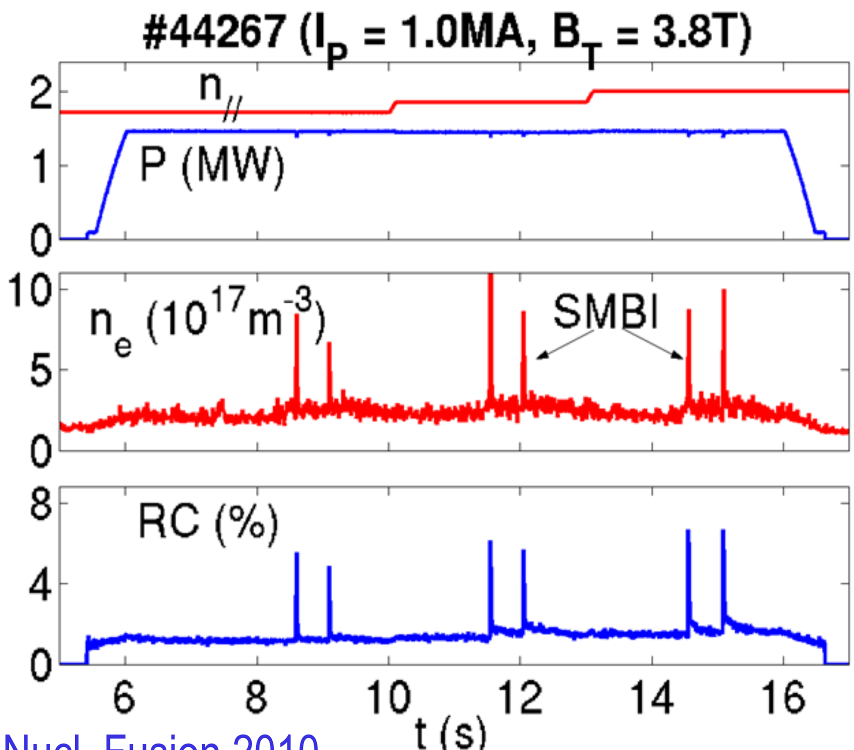


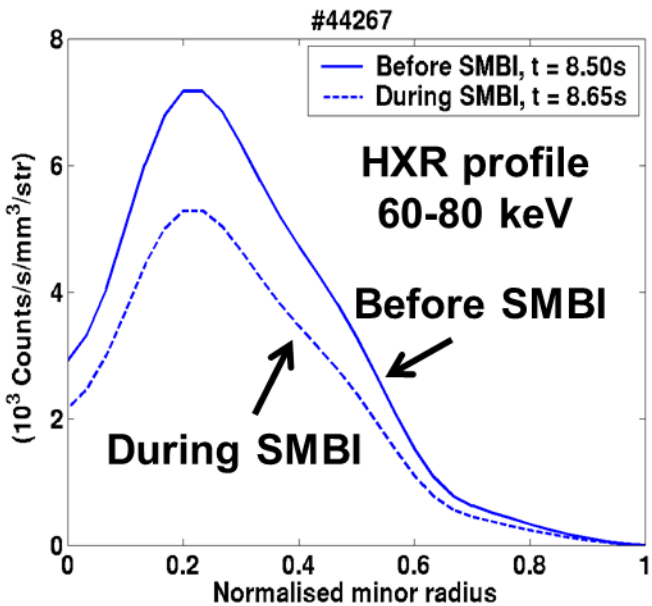
Measured reflection coefficient versus density, compared with calculations with the ALOHA coupling code for different gradients

[Preynas, Nucl. Fusion 2011]
[Hillairet Nucl. Fusion 2010]

RESILIENT COUPLING DURING STRONG EDGE DENSITY PERTURBATIONS

- Power coupled into plasmas maintained by Supersonic Molecular Beam Injection
- No change in LH power deposition shape. Very encouraging for coupling during EMLs





Ekedahl, Nucl. Fusion 2010

Sharma, 37th EPS 2010

OUTLINE

- ❑ INTRODUCTION
- ❑ EXPERIMENTS
- ❑ ADVANCES IN TECHNOLOGY FOR CONTINUOUS WAVE (CW) OPERATION
  - ✓ R&D HIGH POWER KLYSTRONS
  - ✓ ANTENNA
- ❑ LHCD FOR ITER
- ❑ CONCLUSIONS

CONCEPTUAL DESIGN OF AN LHCD SYSTEM FOR ITER

- Not included in the construction phase. Considered for future H&CD upgrade
- Five ITER partners joined efforts (voluntary basis) on conceptual design and feasibility study, incl. scenario development

  CN, EU, IN, KO, and US (Japan follow-up only).
- A pre-design document is available, incl. the conceptual design, costing, schedule, WBS and R&D needs
- Some R&D of RF components were launched by CEA-IRFM
  - Mock up of 5GHz mode converter tested at low power level
  - 5GHz window ongoing manufacturing; high power tests in 2013

ITER LHCD SPECIFICATIONS

- ❑ A 20 MW CW LHCD system in ITER is technically feasible:
  - ➢ one Passive Active Multi-junction (PAM) launcher $N_{//} = 2 \pm 0.2$
  - ➢ 48 CW klystrons 500 kW/5 GHz (3.7 GHz fallback solution)
  - ➢ 48 main transmission lines (could be halved)
  - ➢ 12 HVPS units (likely 90kV/90A)
- ❑ Need 9-10 years, including detailed design and R&D

Hoang, Nucl Fusion 2009
Bécoulet, Fus Eng Design 2011

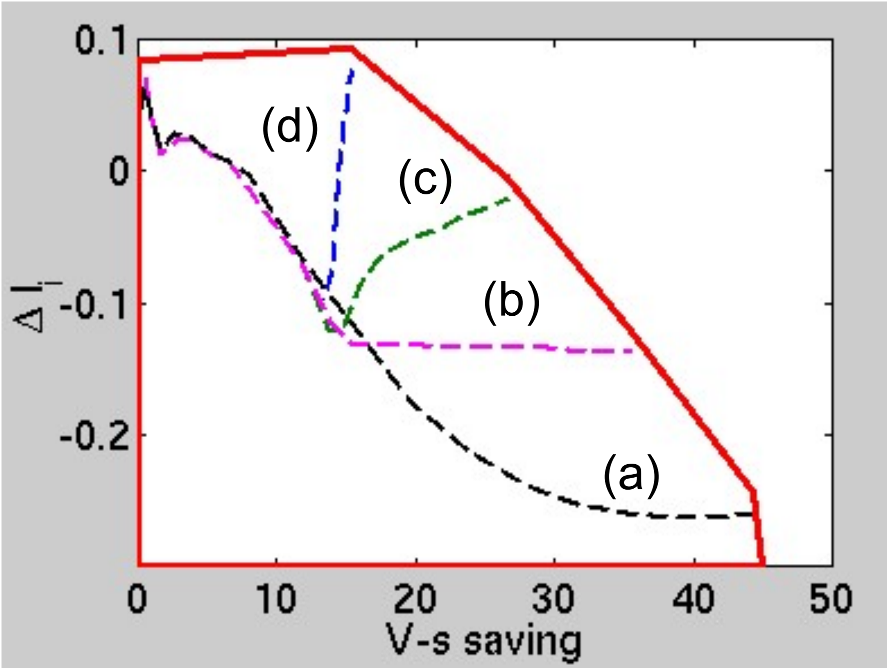
WHICH MISSION(S) FOR LHCD IN ITER?

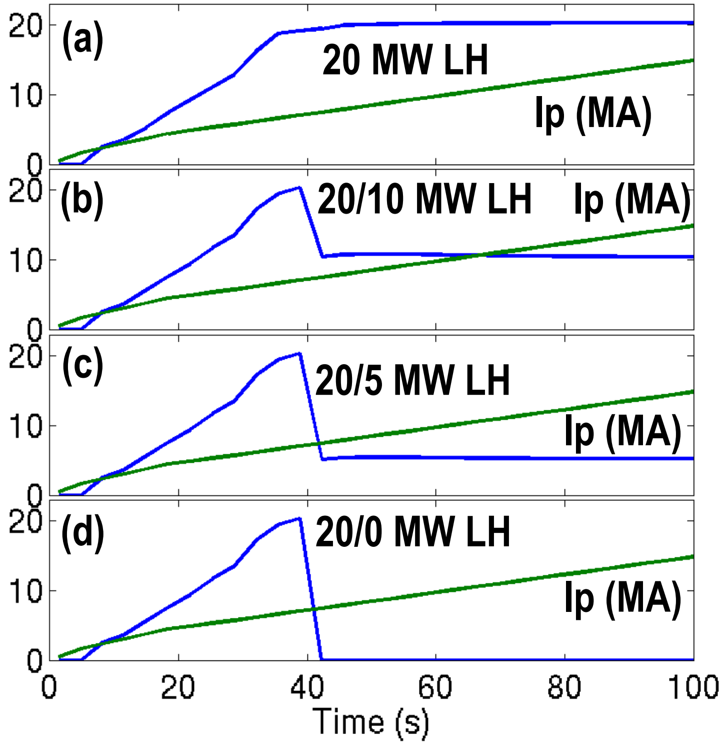
- To extend burn duration -> save Volt-seconds from early current ramp-up phase
- To help accessing and sustaining steady-state plasmas (Advanced Tokamak Physics). Drive far off-axis current (r/a =0.6-0.8), complementarily to Bootstrap Current, NBCD and ECCD.

Hoang, Nucl. Fusion 2009; Kessel, Nucl. Fusion 2009
Kim, PPCF, 2009; Decker Nucl. Fusion2011; Bonoli IAEA-FEC 2006

VOLT-SECOND SAVING IN ITER WITH LHCD

- 20 MW LH save up to 45Wb (~500s of burn duration) during the ramp-up phase of scenario 2.
- V-s saving is accompanied by a decrease of plasma inductance up to $\Delta l_i < 0.3$, helpful for vertical stability control

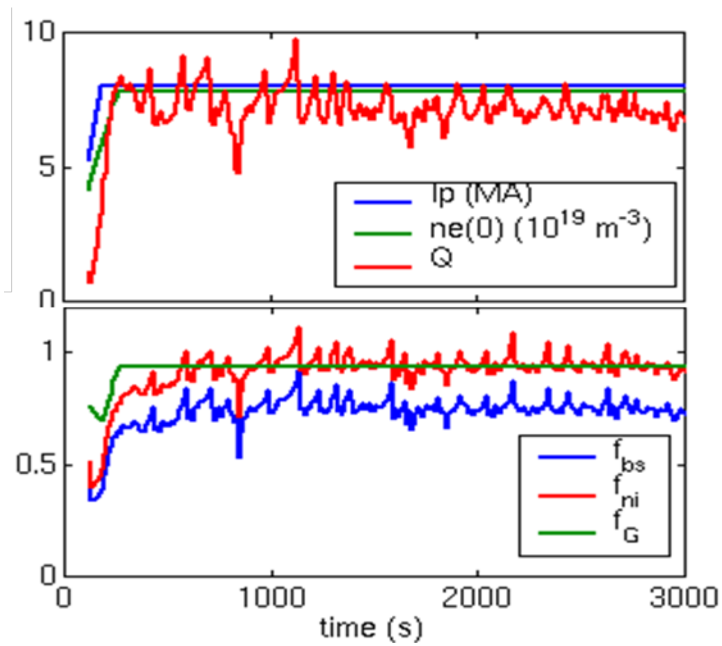


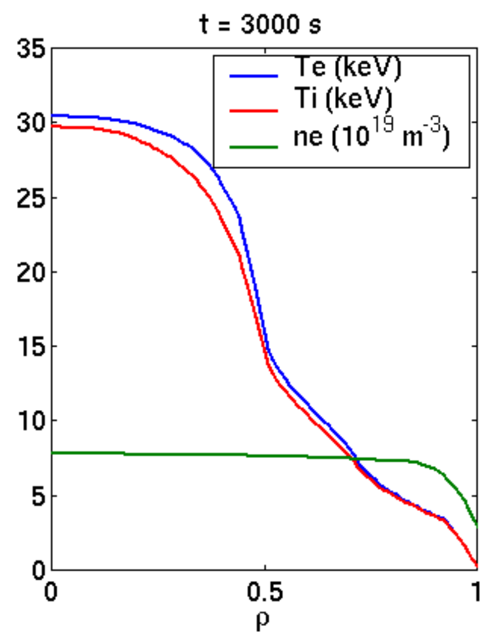


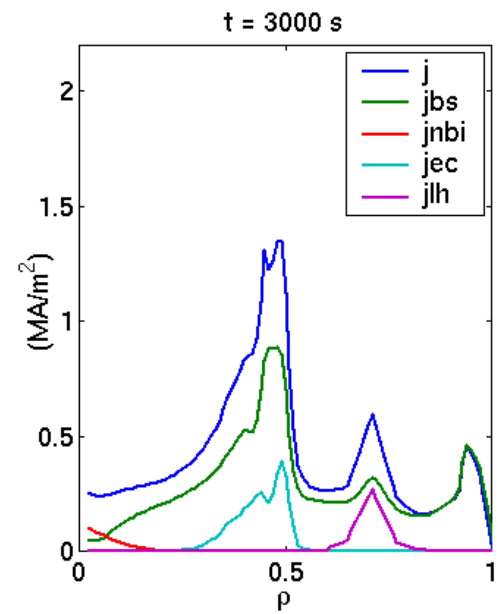
ITER STEADY STATE Q ~7 / 3000S PLASMA SUSTAINED BY RF HCD ONLY

EC+IC+LH: 21+20+12 MW. Non-inductive current fraction ~ 97

- ❑ ECCD triggers and locks ITB position @ r ~ 0.5 via bootstrap
- ❑ LHCD drives current @ 0.6-0.8, required for steady-state



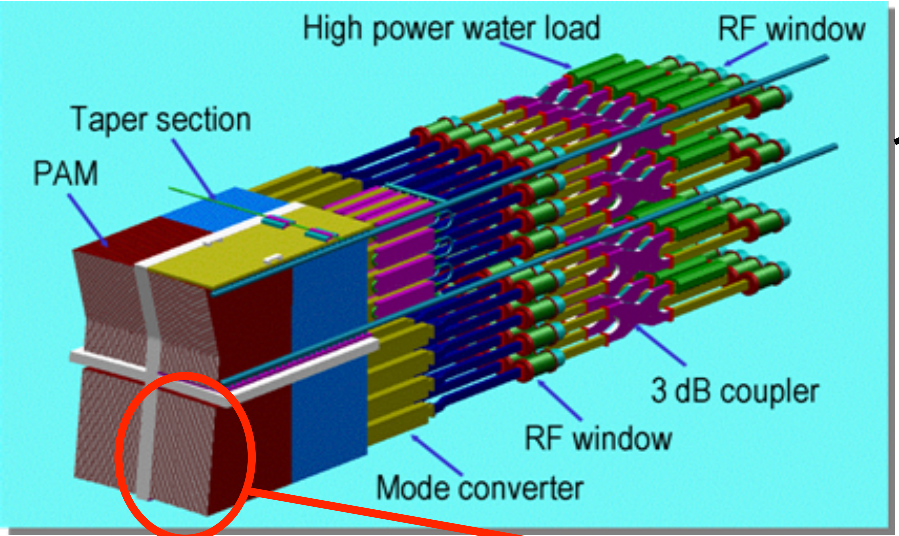


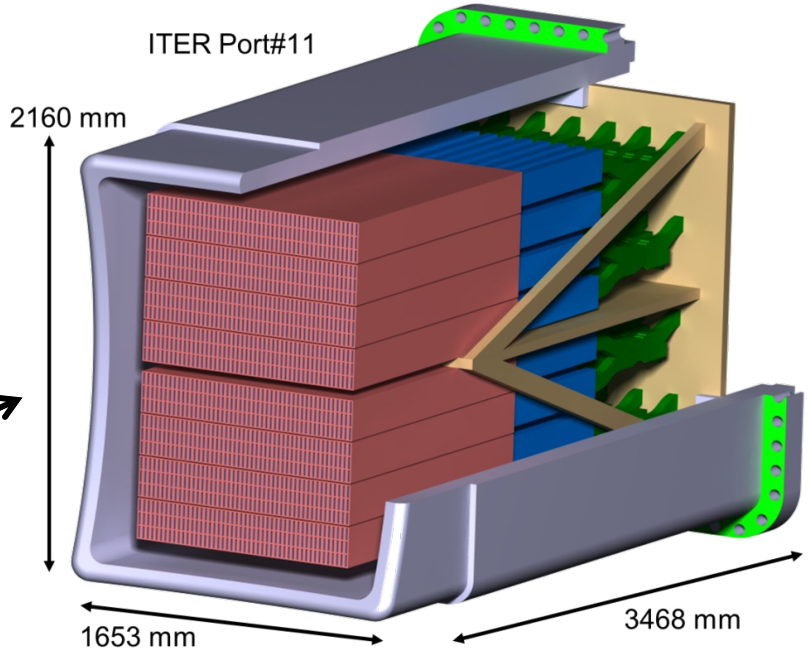


Garcia, Phys Rev Letter 2009

CONCEPTUAL DESIGN OF ITER LHCD LAUNCHER

4 PAM blocks

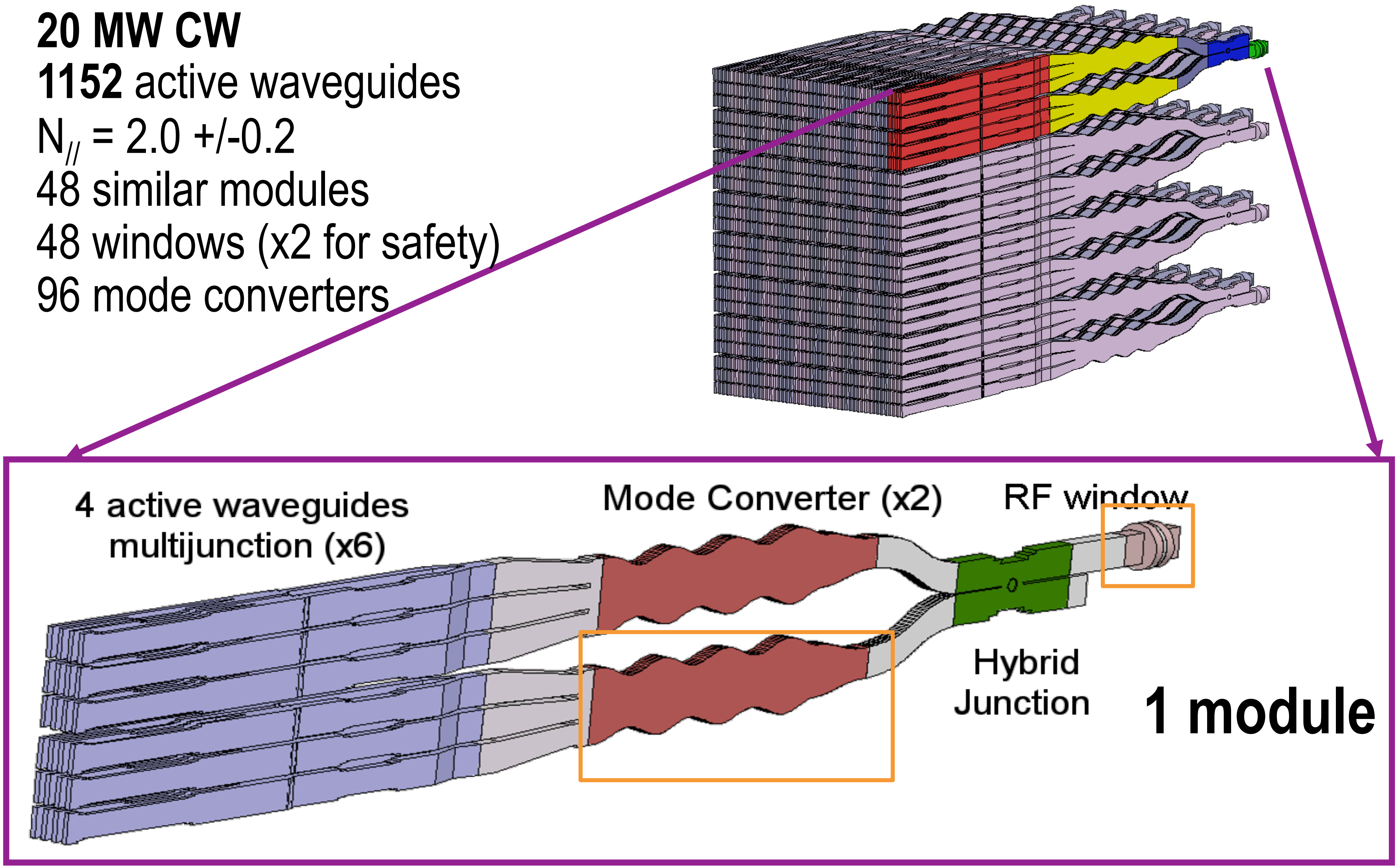




Bibet, Fus. Eng. Design 2003
Mirizzi Fus. Eng. Design 2003

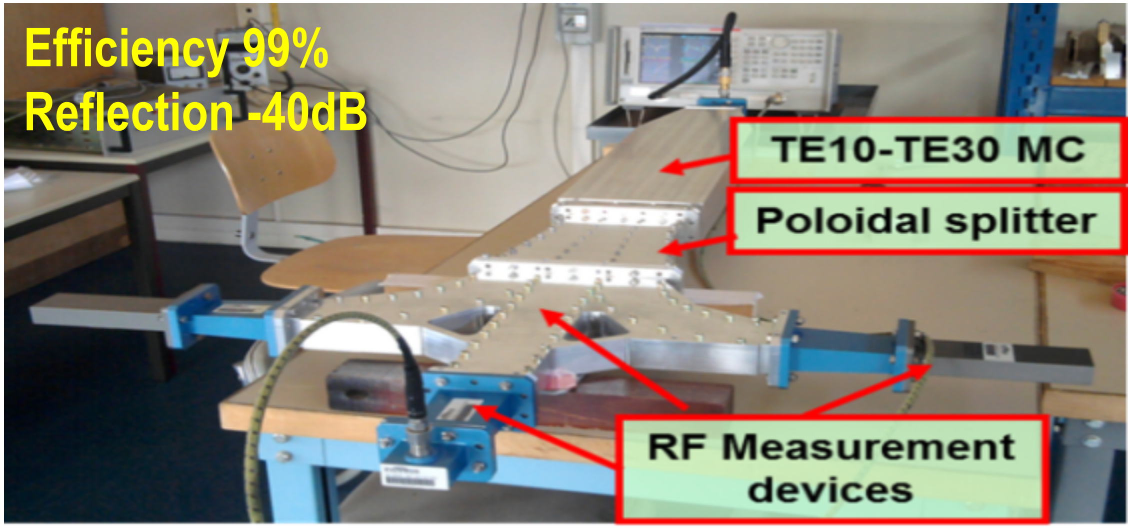
CONCEPTUAL DESIGN OF PAM FOR ITER

20 MW CW
1152 active waveguides
$N_{//}$ = 2.0 +/-0.2
48 similar modules
48 windows (x2 for safety)
96 mode converters



SOME R&D OF RF COMPONENTS FOR ITER AT CEA

- ❑ Mock up of 5GHz mode converter tested at low power level
- ❑ 5GHz BeO window; high power tests in 2013 at NFRI (Korea)

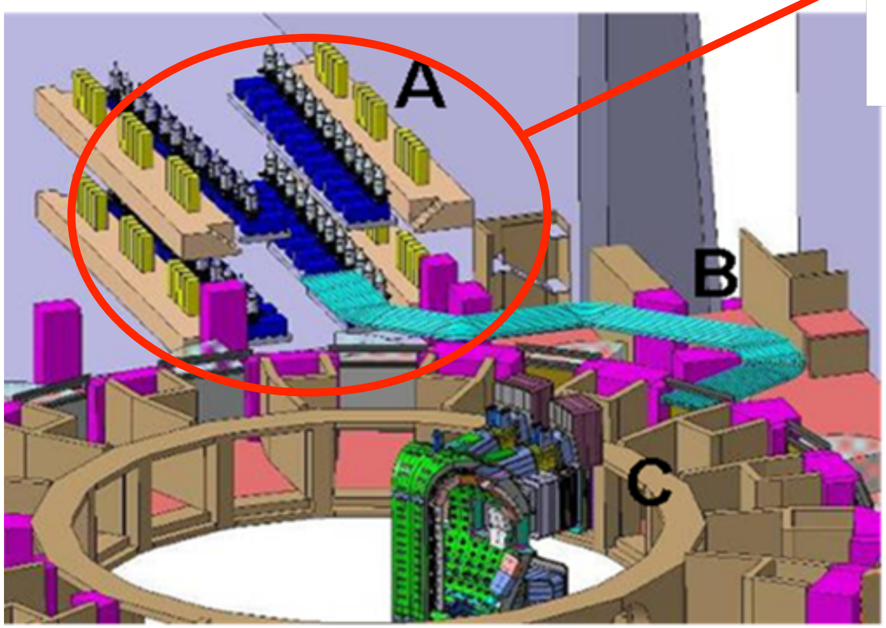


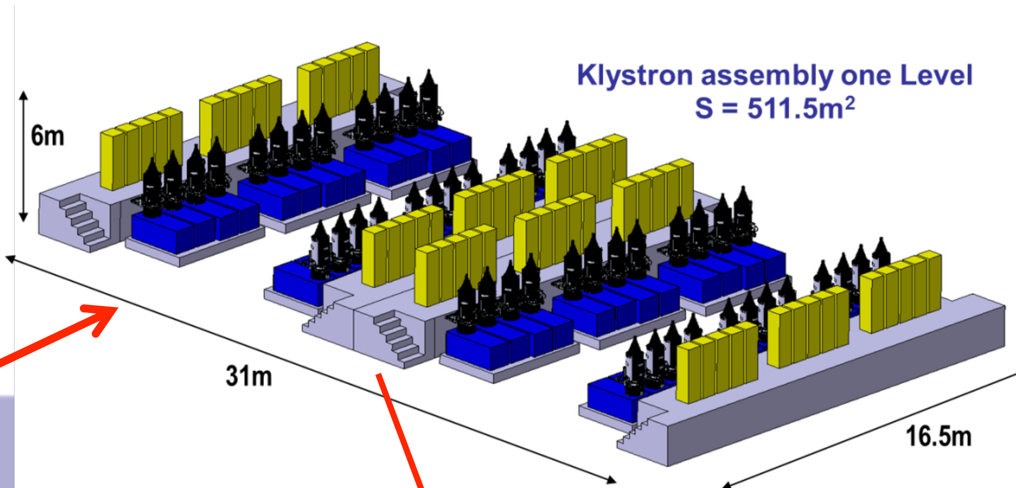
Hillairet Fus Eng Design 2011

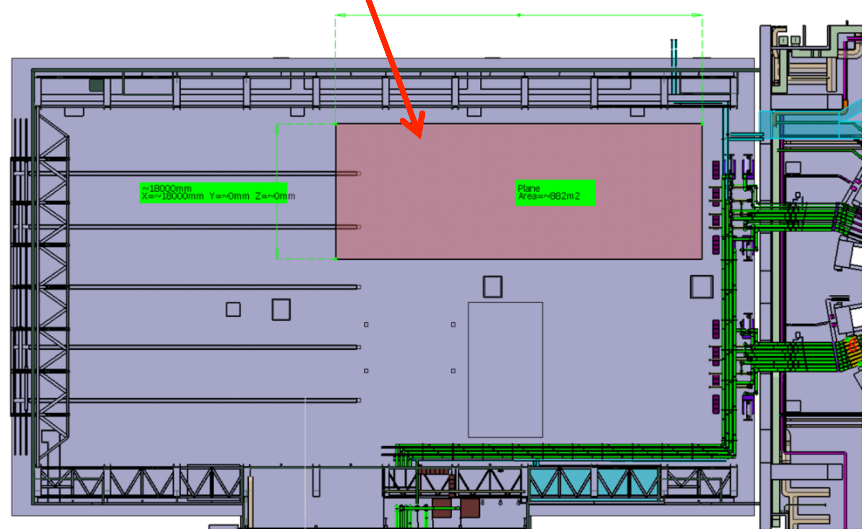
Hillairet 24th IAEA-FEC 2012

INTEGRATION OF 20MW LHCD SYSTEM IN ITER

Port # 11 already booked







ITER

CONCLUSIONS

- ❑ LHCD is a mature and reliable in a large number of tokamaks
- ❑ Significant progress on technology for long pulse operation (high power CW source, antenna), as well as RF modeling and scenario simulation
- ❑ Conceptual design of a 20MW/5GHz LHCD system for ITER, incl. integration aspect in ITER, is now available for possible upgrade of H&CD systems

…SOME REFERENCES

- 'Advances in Lower Hybrid Current Drive for Tokamak Long Pulse Operation: Technology and Physics' G.T. Hoang. http://www.jspf.or.jp/PFR/PFR_articles/pfr2012S1/pfr2012_07-2502140.html
- Steady State Long Pulse Tokamak Operation Using Lower Hybrid Current Drive
  A.Bécoulet, G.T Hoang Fus Eng Design 2011
- A lower hybrid current drive system for ITER , G.T. Hoang Nucl Fusion 2009

Papers related to the conceptual design of LHCD system for ITER: Fusion Eng. And Design 2011

- Design of the Main Transmission Line for the ITER-relevant LHCD System, Mirizzi et al.
- Mode filters for oversized transmission lines of ITER-relevant LHCD system, Ceccuzzi et al.
- Bends in oversized rectangular waveguide, Meschino et al.
- Thermal and Mechanical Analysis of ITER-relevant LHCD Antenna elements, Marfisi et al.
- Proposed high voltage power supply for the ITER-relevant LHCD system, Sharma et al.
- RF Modeling of the ITER-relevant Lower Hybrid antenna, Hillairet et al.
- Benchmark of coupling codes (ALOHA, TOPLHA GRILL3D) with ITER-relevant Lower Hybrid antenna, Milanesio et al.