DE LA RECHERCHE À L'INDUSTRIE

ONGOING R&D TOWARDS A NEW GENERATION OF NEUTRAL BEAM HEATING SYSTEMS FOR FUTURE FUSION REACTORS

ICIS 2017 Conference

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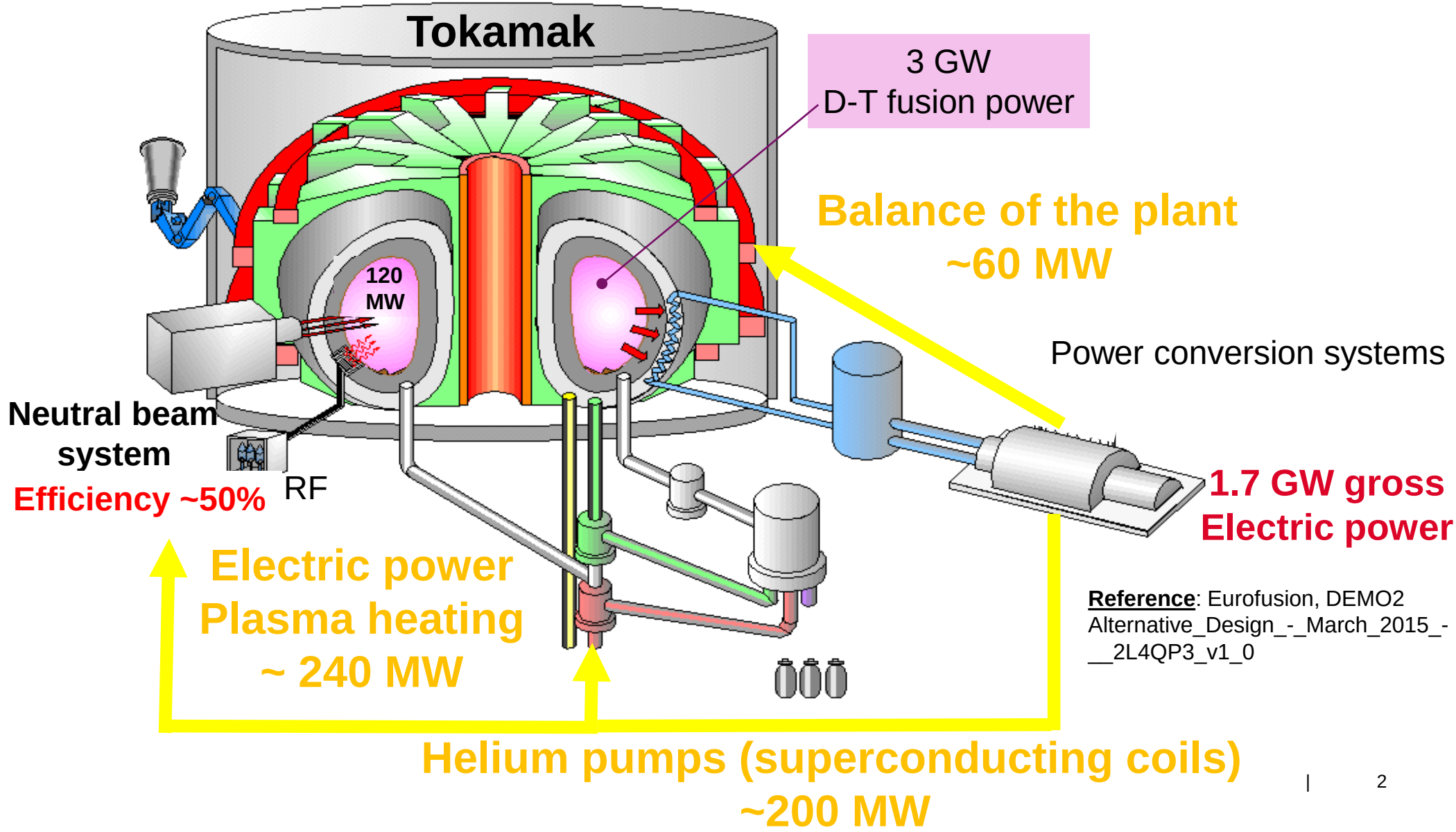
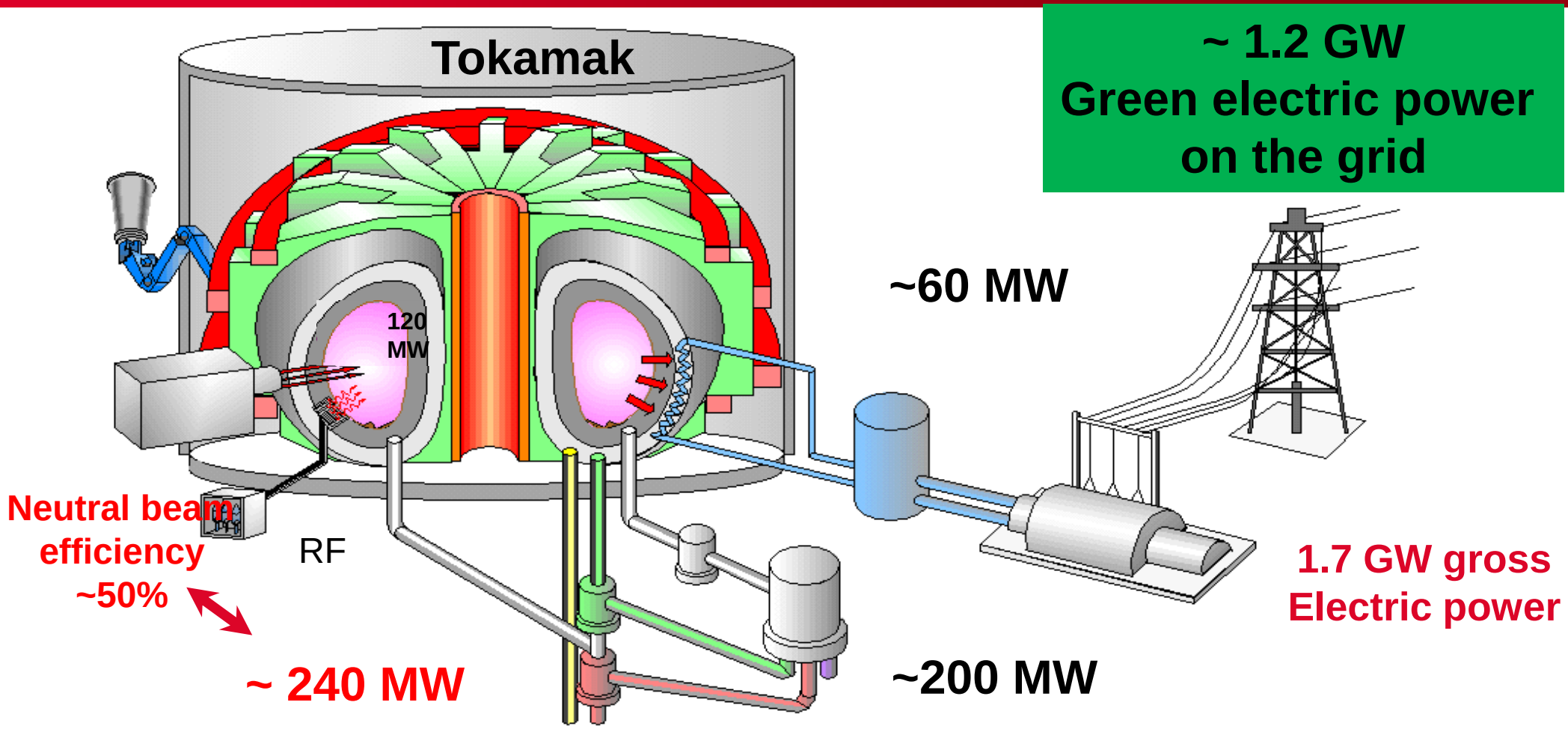
STEADY STATE FUSION REACTOR "RECIRCULATING ELECTRIC POWER "



Reference: Eurofusion, DEMO2 Alternative_Design_-_March_2015_-__2L4QP3_v1_0

RECIRCULATING ELECTRIC POWER IN THE PLANT

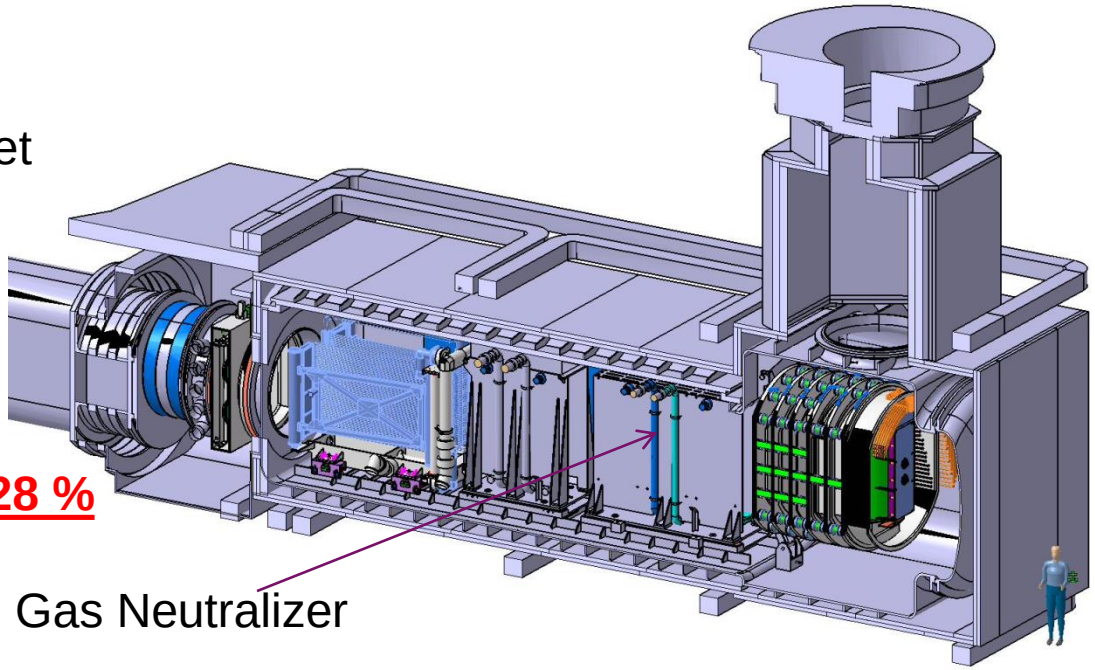


Neutral Beam system **efficiency** ⇔ Main penalty on the electricity production and cost

Challenge : Achievement of powerful neutral beams with efficiency > 50%

Efficiency of conventional Neutral Beam systems (ITER type)

- 1 MeV D^- beam neutralization on gas target
- Only 55% of neutralization rate
- Overall NB system efficiency **lower than 28 %**



- **The goal of ITER is not to produce electricity !**
- **For future reactors: ITER NBI system efficiency too low !**

Need to explore neutralization system with high conversion rate

BEAM PHOTO-NEUTRALIZATION

Photo-neutralization seems ideal

- **No gas injection => Strong reduction of D^- losses**
- **Potential High neutralization rate (η> 80%)**

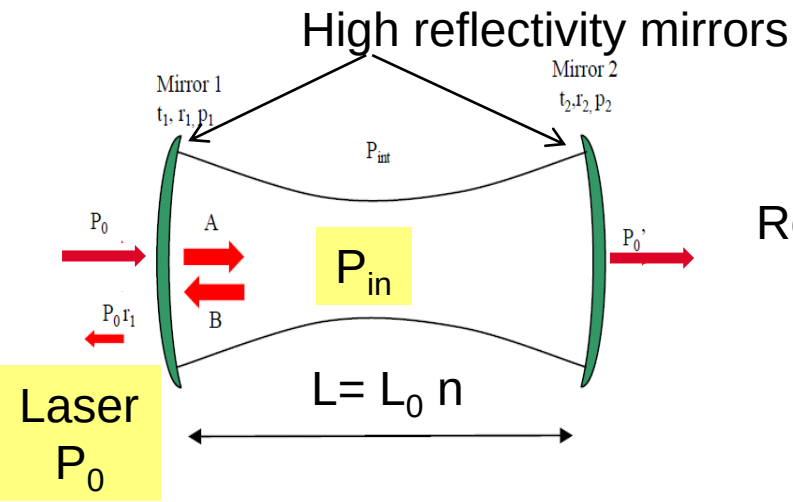
But

- **Low photo-detachment cross-section**

$$\sigma \sim 3.6 \ to \ 4.5 \, . \, 10^{\wedge -21} \ m^{\wedge 2} \text{ for } \lambda = 1064 \text{ nm}$$

Photo-neutralization requires photon flux in the MW range

High photon flux ⇔ Resonant Fabry-Perot cavity



Resonance ⇔ $2\ L = q\ \lambda$ ⇔ Constructive interferences

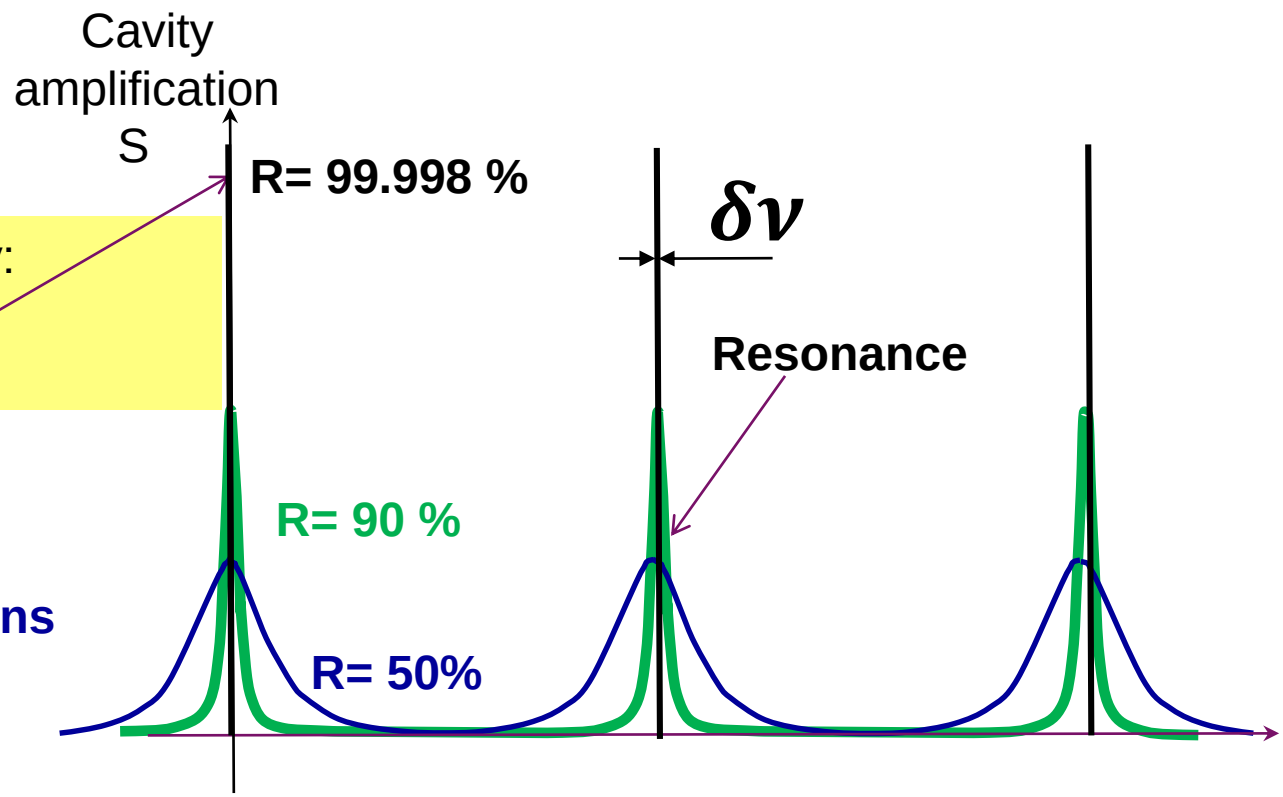
Photon power stored within the cavity:

$$P_{in} = P_0 \times S$$

P_0 = 1 kW, S ~3000, P_{in}~ 3 MW

P_{in} ↗ => $\delta\nu$ ↘

High cavity sensitivity to variations of the optical length:
vibrations, etc.



Advanced stabilizing technique Gravitational Waves Detectors (GrWD)

- Locking of the cavity resonance technique: **Pound-Drever-Hall method**

  Cavity Resonance when: $2\,L = q\,\lambda$

  $\delta L \propto \delta\lambda$

  Cavity vibration

  Active feedback on the external Laser wavelength

Mature technology : First GrW detected in 2016 on LIGO facilities (USA):

$$\delta L/L \sim 10^{-21}$$

Photo-neutralizer: Requirements on the optical length variation strongly released

$$\delta L/L \sim 10^{-12}\ \mathrm{m\ Hz^{-1/2}}\ @\ 1\ \mathrm{kHz}$$

Achievable with available commercial technology !

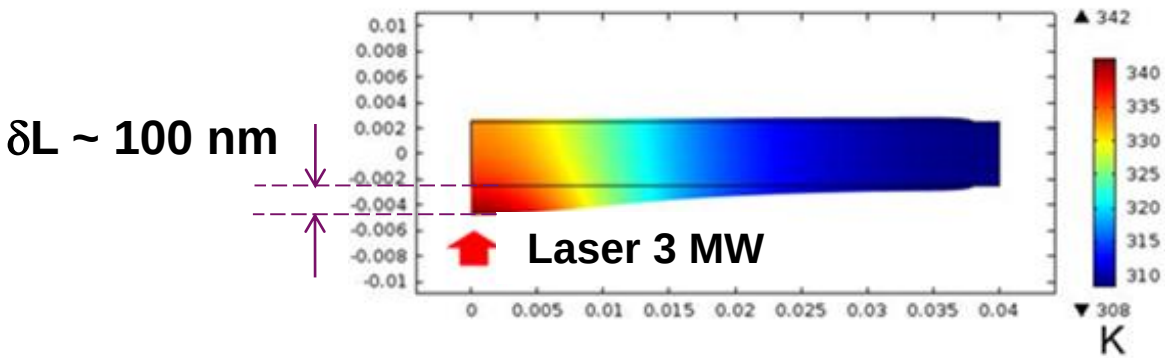
Mirror thermo-mechanical deformation under high photon power (CW regime)

- Mirror coating absorption rate ~ 1 ppm

  3 MW of photon power => 3 W of thermal power absorbed by the mirror

  => Thermal distortion of the mirror surface

Mirror temperature distribution

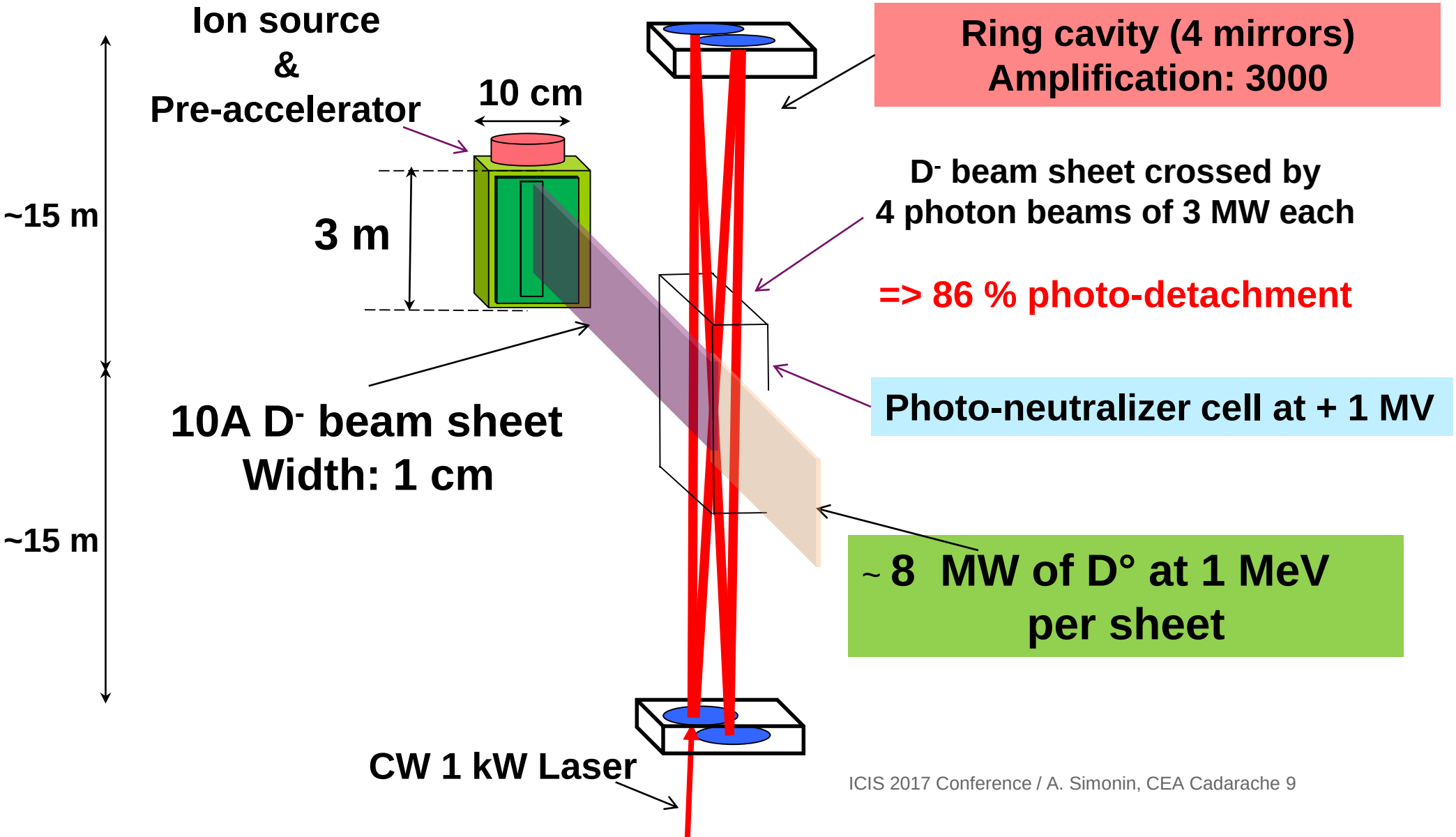


Reference: D. Fiorucci; Ph-D thesis
Nice-Sophia Antipolis University,
Côte d'Azur Observatory
Nice, France; June 2015

Mirror distortion (peak 100 nm) => wave deformation => photon scattering (losses) !

Need to implement adaptive optics to keep the mirror planarity ~1 nm range

Principle of a photo-neutralization Based NB system



Implantation of the NB system on the reactor (Top view)

Modular concept

⇒ **Six beamlines in // per tank**

⇒ **45 MW D° per tank**

⇒ **Overall efficiency: ~70%**

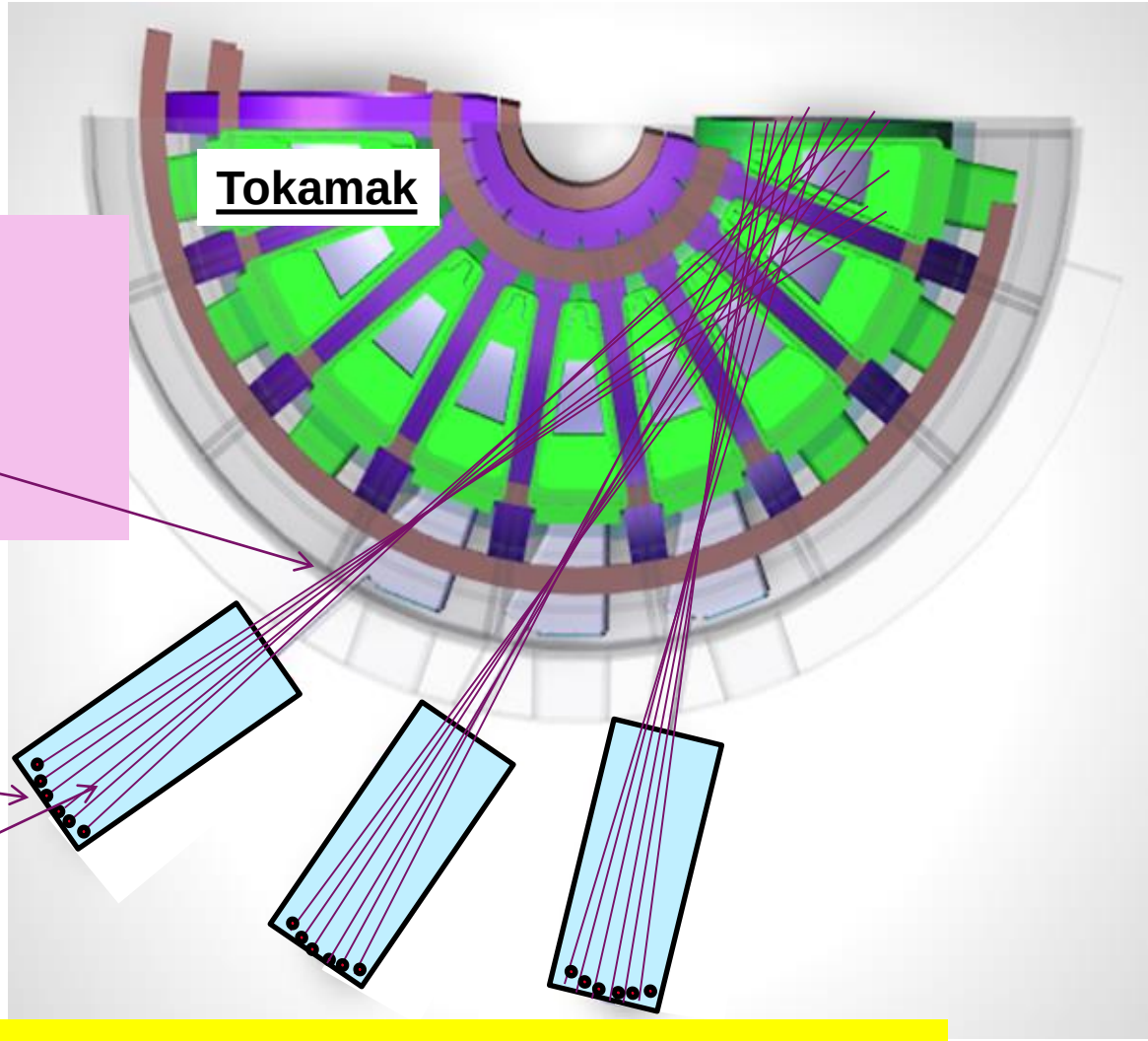


Photo-neutralization allows to achieve powerful neutral beam with high efficiency

Implantation of the NB system on the reactor
(side view)

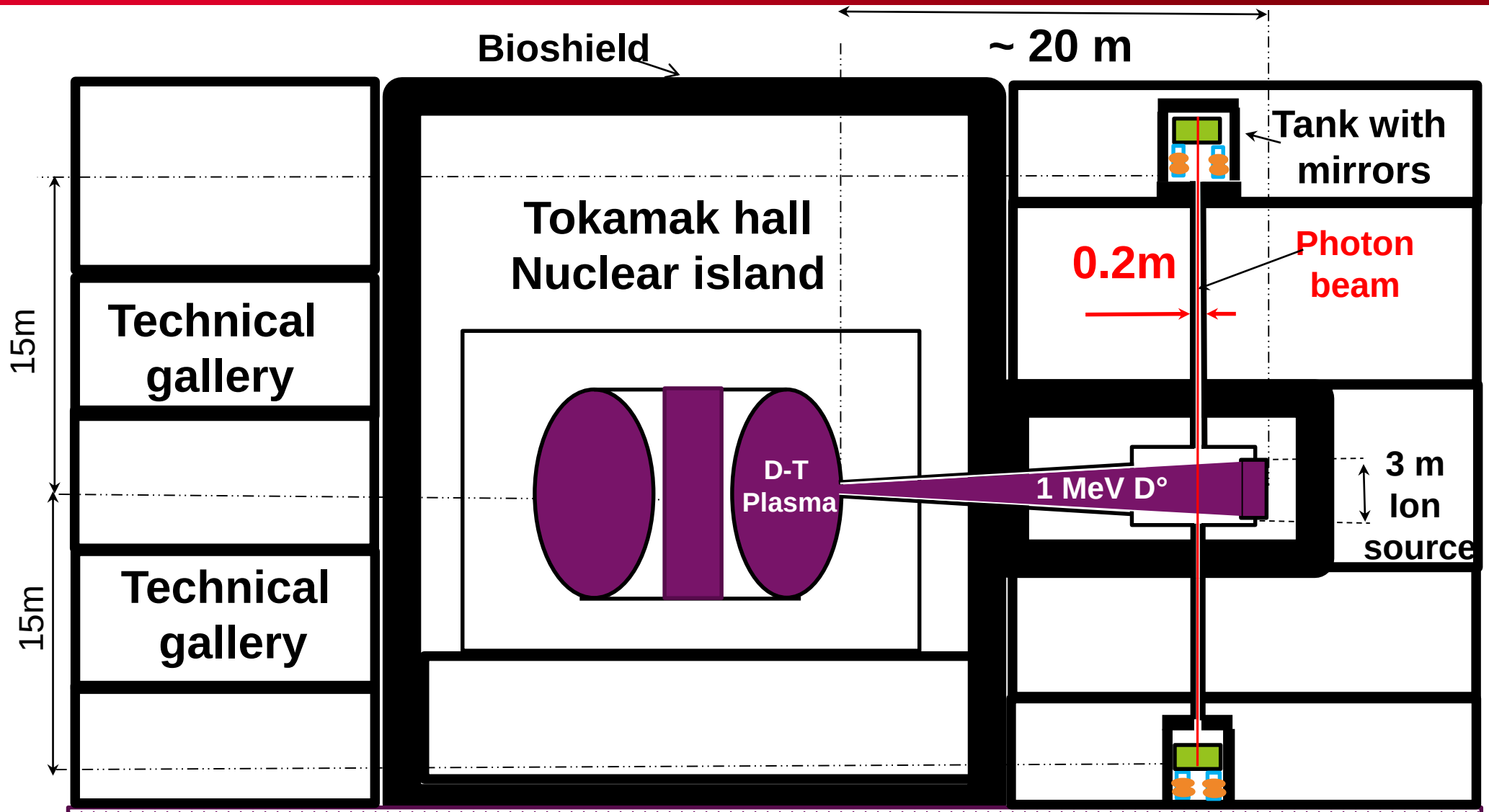
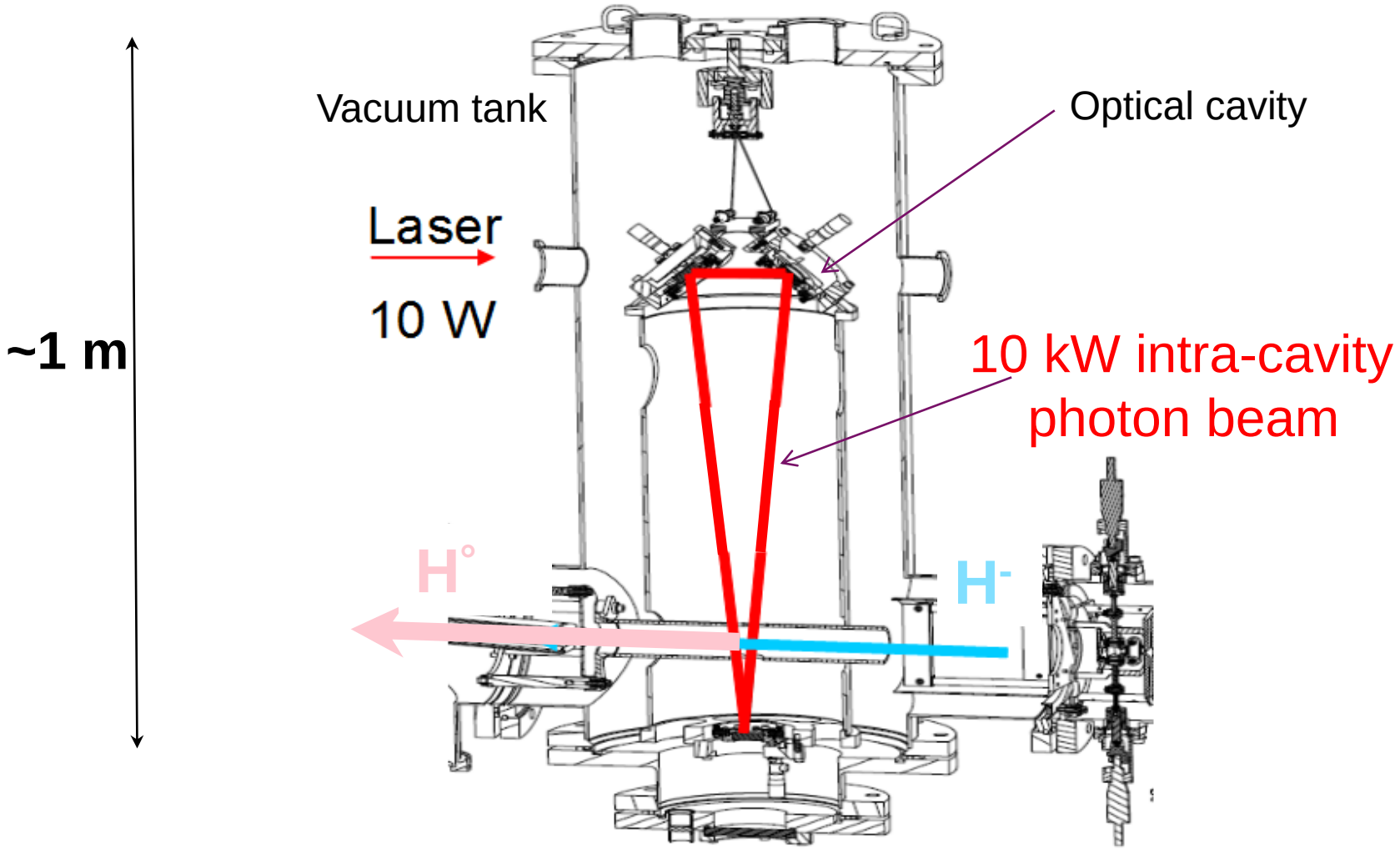


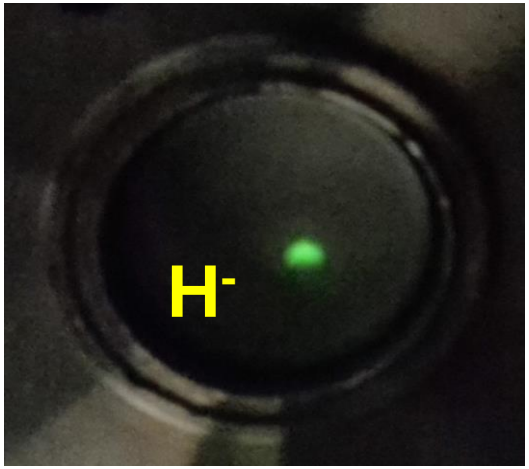
Photo-neutralization experiment in cavity



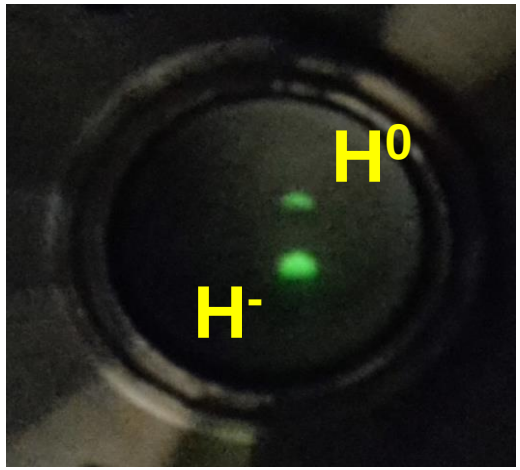
➢ **H^- beam: 1 keV and 1 mm diameter**

Photo-neutralization experiment in cavity
Experimental results

Photon power 0 kW

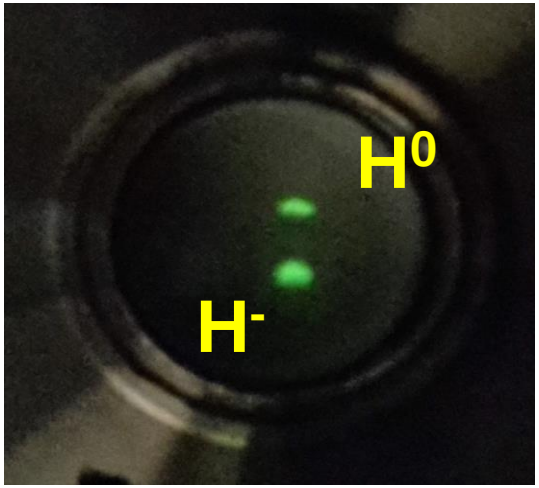


Photon power 13 kW



Observation of H^- and H° on micro-channel detectors

Photon power 23 kW

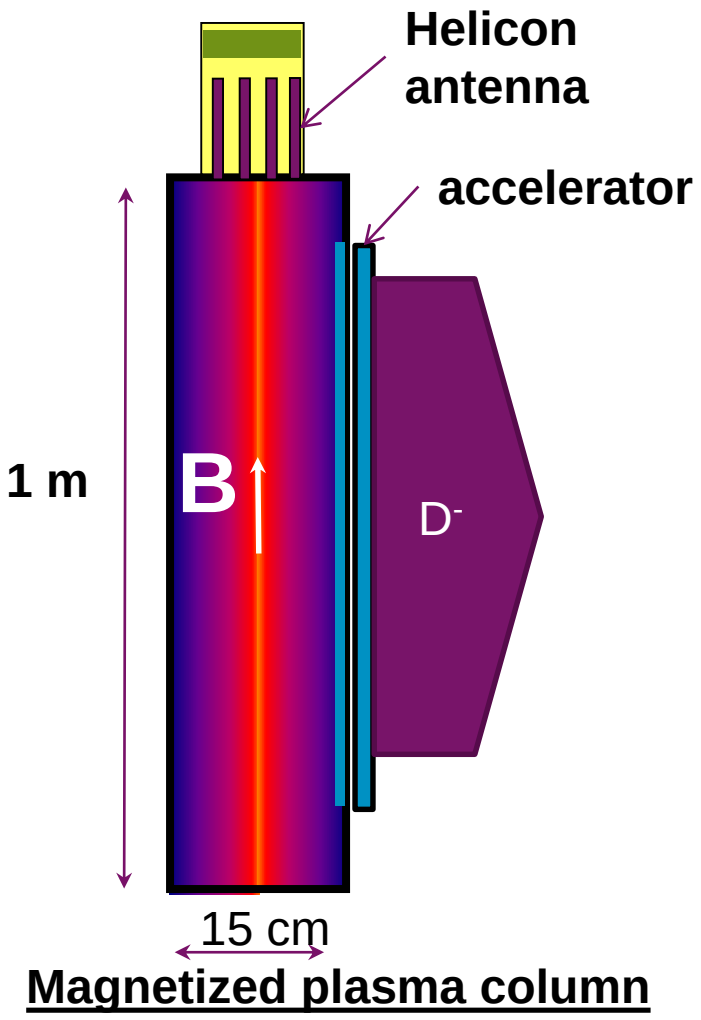


- **50 % photo-detachment achieved in CW regime**
- **In agreement with cross section**

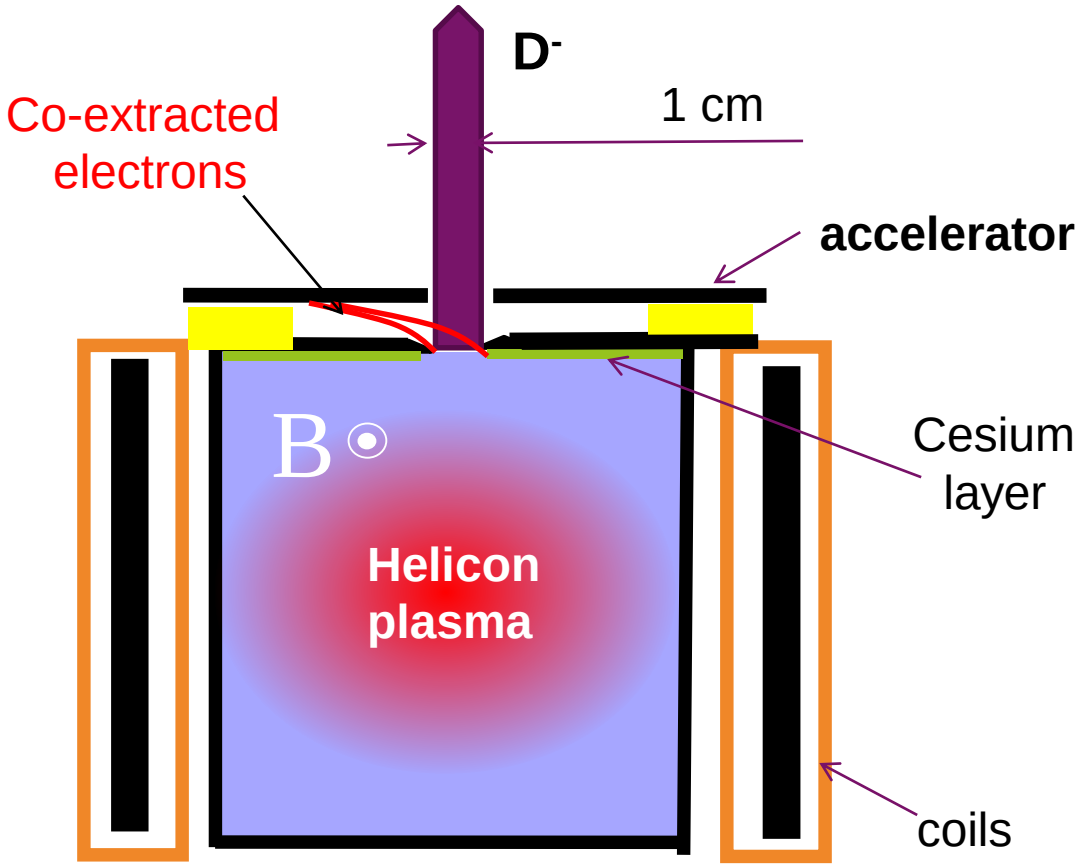
<u>Publication:</u> « Saturation of the photoneutralization of a H^- beam in continuous operation »; D. Bresteau, C. Blondel, C. Drag; Rev. Sci. Instrum.; 2017; in press.

Ion source development for photo-neutralization based NB system

Blade-like negative ion source concept



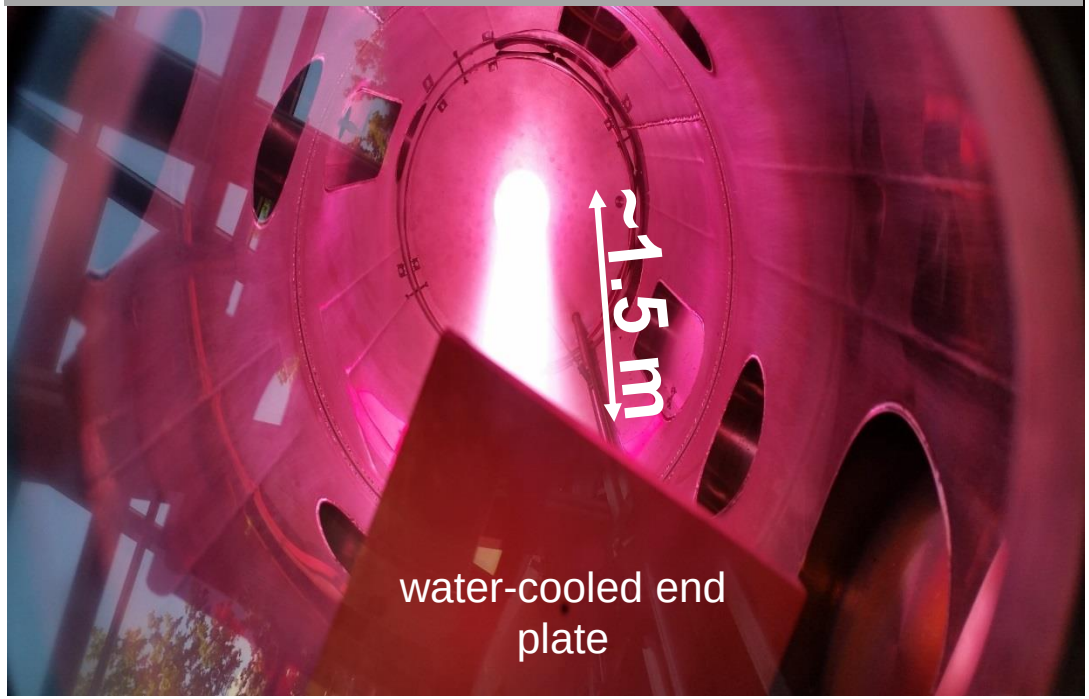
Side view



Horizontal cross section

Development of a 10 kW helicon antenna (Bird-cage type) at RAID testbed (EPFL)

A 3 kW, 0.3 Pa, B= 12 mT, H_2 plasma jet



Further details: Talk R. Agnello (EPFL); Tuesday, 17th October; 15h20

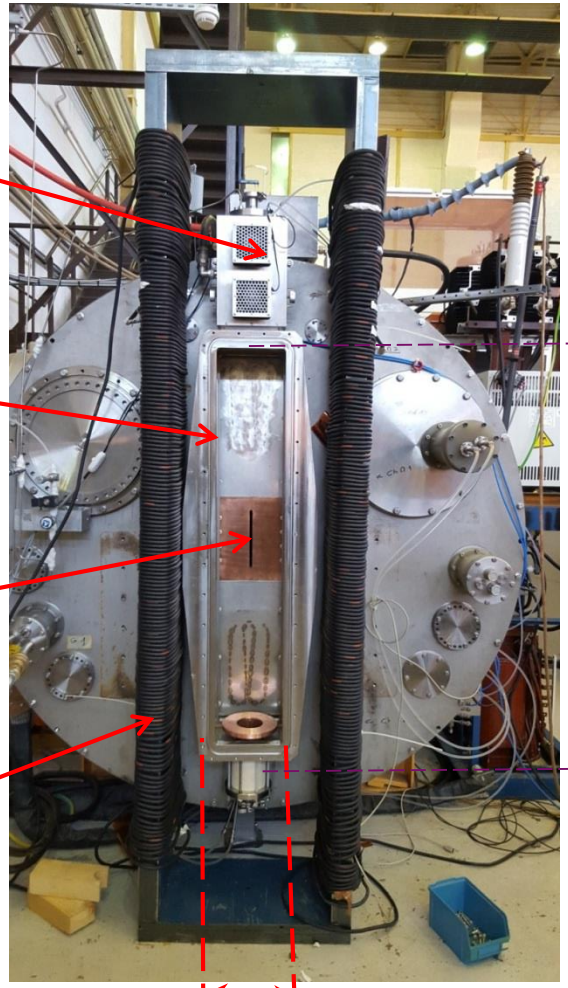
Ion source at IRFM with the helicon antenna

10 kW helicon antenna

Ion source
1.2 m high
0.1 m width

Accelerator grid
Blade-like beam (1 cm width)

Lateral coils
B~10 mT



1.2 m

10cm

First experimental results: Poster I. Morgal (IRFM); Tuesday, 17th October ; 16h00

Conclusions and perspectives

Conclusions

- Photo-neutralization is the only commercial solution for **steady state reactors:**
  - Advanced performances
    - **High neutral power: up to 45 MW per beam tank**
    - **High wall-plug efficiency: ~70 %**

Perspectives:

Up to 2020: Finalise the ongoing feasibility studies

- **Study of the mirror thermal effects and compensation (adaptive optics)**
- **Continuation of the R&D on helicon antenna & blade-like beams**

After 2020:

- **Proposal for a full scale high power (MW range) optical cavity**
- **The project would imply the involvement of experts in GrW detectors**

Thank for your attention !!

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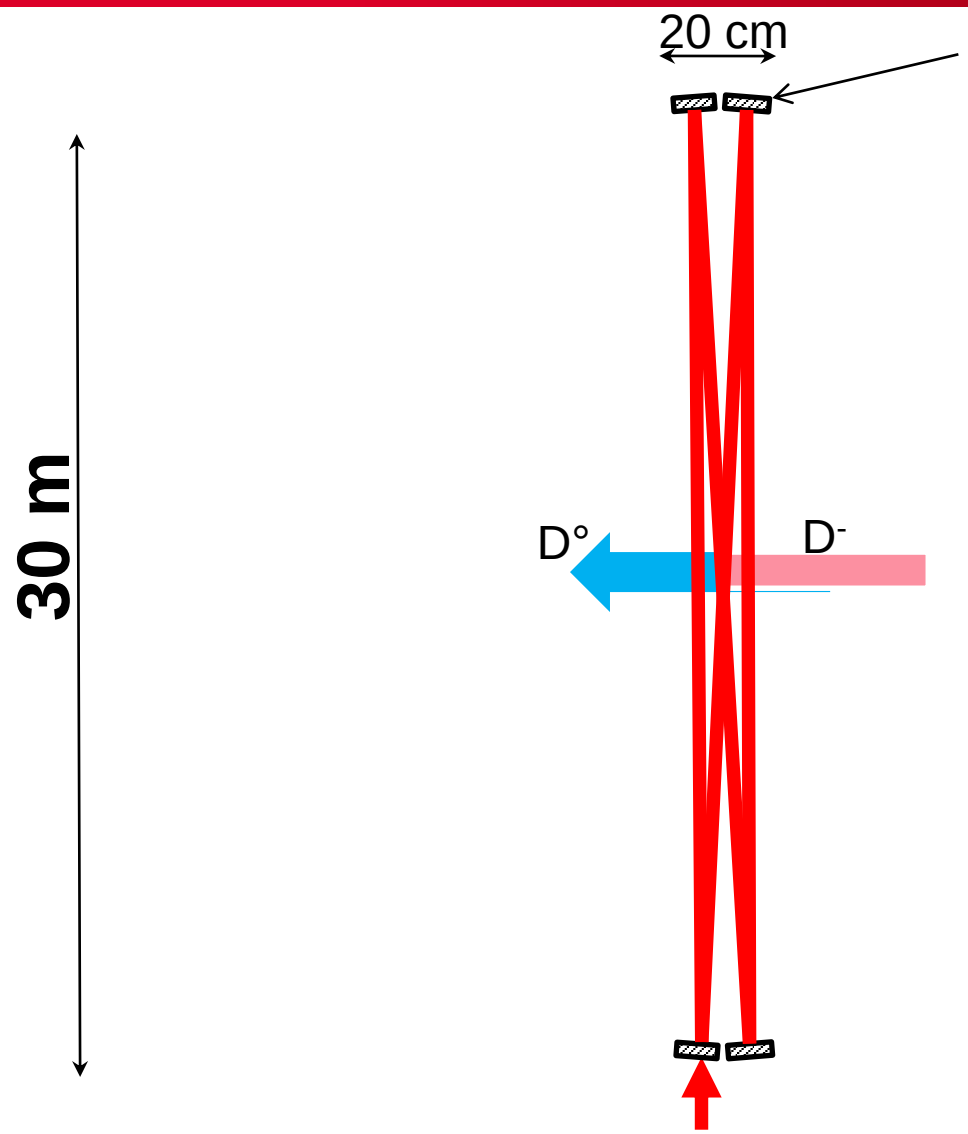
3 MW optical cavity specifications



Photon power in cavity: 3 MW

- Enhancement factor: 3000
- Cavity bandwidth: $\delta\nu$~150 Hz
- Highly stabilized Laser: $\delta\nu/\nu \sim 10^{-24}$

Ring (recycling) cavity

- Roundtrip: L_0 = 120 m
- Photon beam width at FWHM: 1cm

Advanced mirrors:

- Reflectivity: 99.998 %
- Planeity: ~1 nm
- Rugosity: ~0.1 nm
- Coating absorption rate: < 1 ppm

Highly stabilized CW Laser, P_0 ~1 kW

Comparison of the main specifications between the GrW detectors and the photo-neutralizer.

Color code:
green: available technology;
red: future R&D objectives

	GrWD	Photo-neutralizer
Setup	Two cavities in interference, common mode : frequency reference	A single cavity : frequency reference
Mechanical vibration mitigation level	**Achieved** < 10^{-20} m $Hz^{-1/2}$ @ 100 Hz (limited by fundamental noise)	10^{-12} m $Hz^{-1/2}$ @ 1 kHz
Stored photon power	**Achieved:** 100 kW on LIGO Advanced LIGO **objective:** 700 kW	**3 MW**
Cavity	Roundtrip: 6000 m (linear cavity)	Roundtrip: 120 m (ring cavity)
Mirrors	**Achieved** Diameter: ~30 cm Planeity: < 0.5 nm RMS over Ø=15 cm Roughness: < 0.1 nm RMS Coating absorption: 1 ppm	Diameter: 10 cm Planeity: 1 nm RMS over Ø=5 cm Roughness: 0.1 nm RMS Coating absorption: 1 ppm
External CW Laser (λ=1064 nm)	**Achieved** Power : 200 W Single mode, single frequency, Locked on the cavity	**Power : 1000 W** **Single mode, single frequency, Locked on the cavity**

Gravitational Waves detection in 2016
Image Credit: Caltech/MIT/LIGO Lab

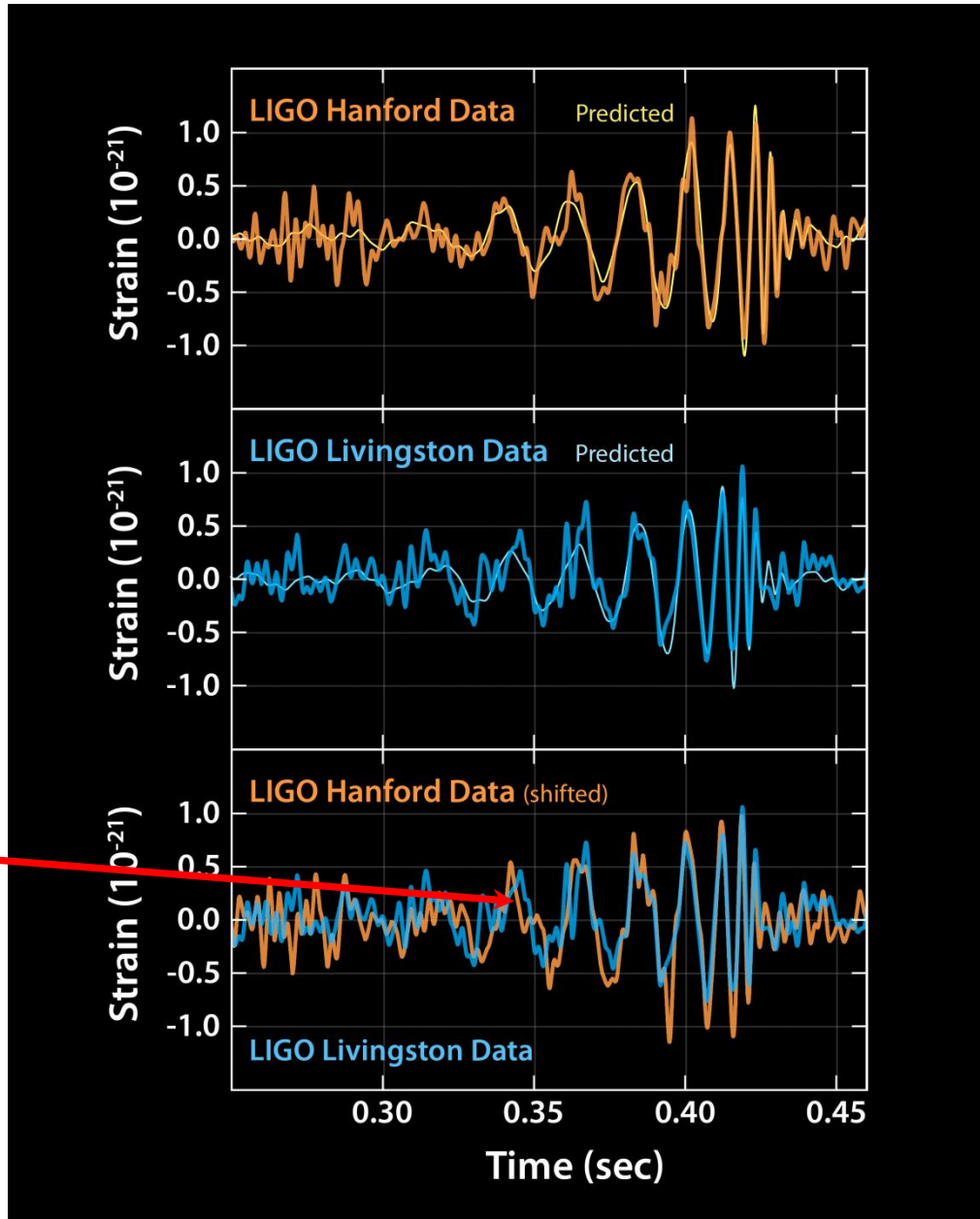
Signals of GrW detected by the twin LIGO observatories:

-) Livingston, Louisiana

-) Hanford, Washington

Superposition of the two signals
⇒ Same event

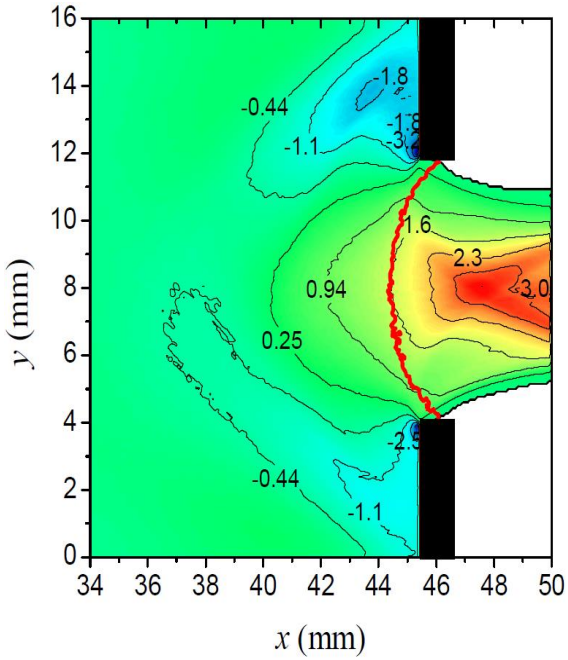
⇒ Detection level: $\delta L \sim 10^{-21}$ m



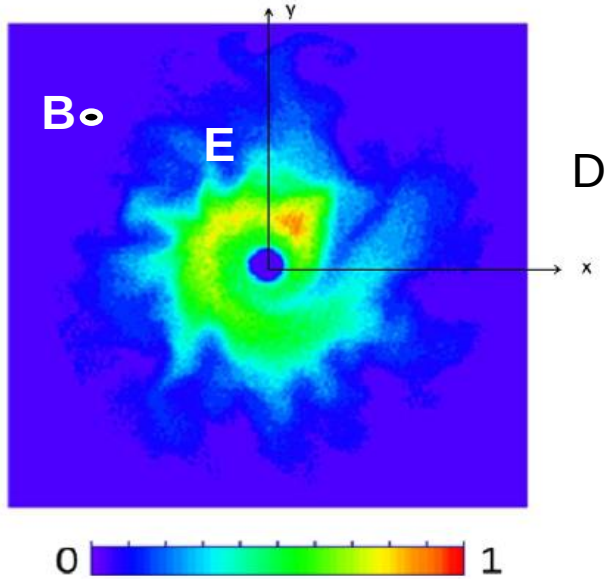
Laplace laboratory (Toulouse, France)
Development of numerical models for Cybele

⇒ Physics of the magnetized plasma column
⇒ Physics of the negative ion extraction

H^- beam extraction



2D simulation PIC MCC model of the negative ion extraction from the magnetized plasma (side vie



2D simulation PIC MCC model of the magnetized plasma column (Horizontal cross section)

Diamagnetic plasma rotation
E x **B**

B=7 mT, E ~1 V/cm

Validation by experiment on Cybele