High-power CW Transmission Systems and Launchers

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- Introduction: CW / long-pulse transmission systems for ECRH
- HE11 corrugated waveguide transmission
- Beam waveguide transmission
- Matching problems
- Diagnostic components: CW power monitors and CW loads
- Launchers and in-vessel components: W7-X, ITER, Tore Supra
- Summary

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K. Sakamoto and K. Takahashi, JAERI, Mito
R. Magne and M. Lennholm, CEA Cadarache

Some present and future long-pulse / CW ECRH / ECCD Systems:

DIII-D	110 GHz	6 gyrotrons		3.5 MW / 3 sec	in plasma
JT-60	110 GHz	4 gyrotrons		3 MW / 3 sec	in plasma
Tore Supra	118 GHz	> 2 gyrotrons		0.71 MW / 25 sec	in plasma
LHD	84 / 168 GHz	7 pulsed + 1 CW gyrotron		0.072 / 766 sec	in plasma
W7-X	140 GHz	10 gyrotrons	design:	10 MW CW inst.,	in construction
ITER	170 GHz	24 gyrotrons	design:	24 MW CW inst.,	in development

- Typical goals are 1 MW / 10 sec .... CW per line
- Developments for ITER aim at 2 MW CW per line

==> corrugated waveguides (HE11 mode)

==> (multi)-beam waveguides (TEM00 mode)

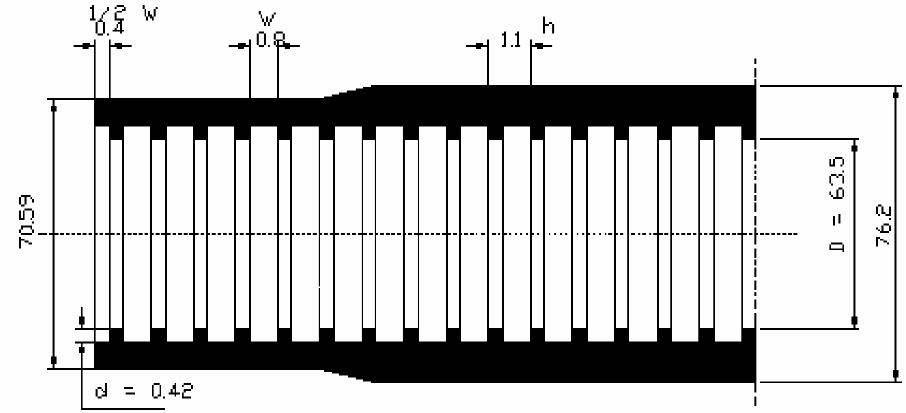
==> launchers with toroidal and poloidal steering

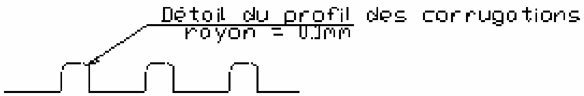
For high efficiency and high reliability: low loss !

Corrugated waveguide transmission

Propagation of HE11 mode

$$E(r,z) \quad \propto \quad J_0\left(\frac{2.405 \cdot r}{a}\right) \cdot e^{ik_{11}z}$$





waveguide loss for HE11: **==> low loss**

loss increases with mode number **==> high-order-mode filtering**

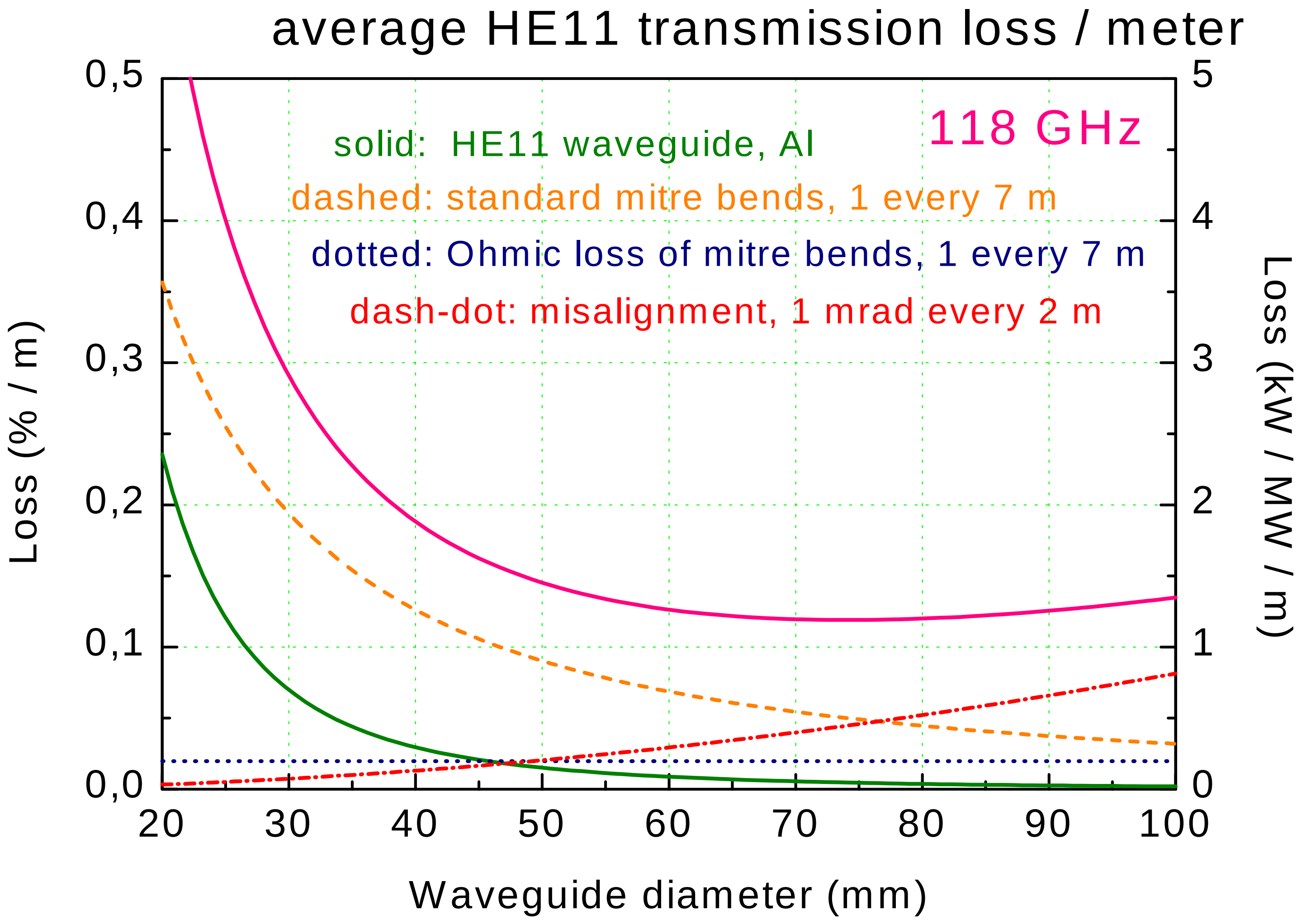
curvature / tilt of waveguide **==> mode conversion loss (low-order modes)**

mitre bends **==> mode conv. Loss (mainly high-order modes)**

==> ohmic loss

Transmission in air: ==> atmospheric absorption

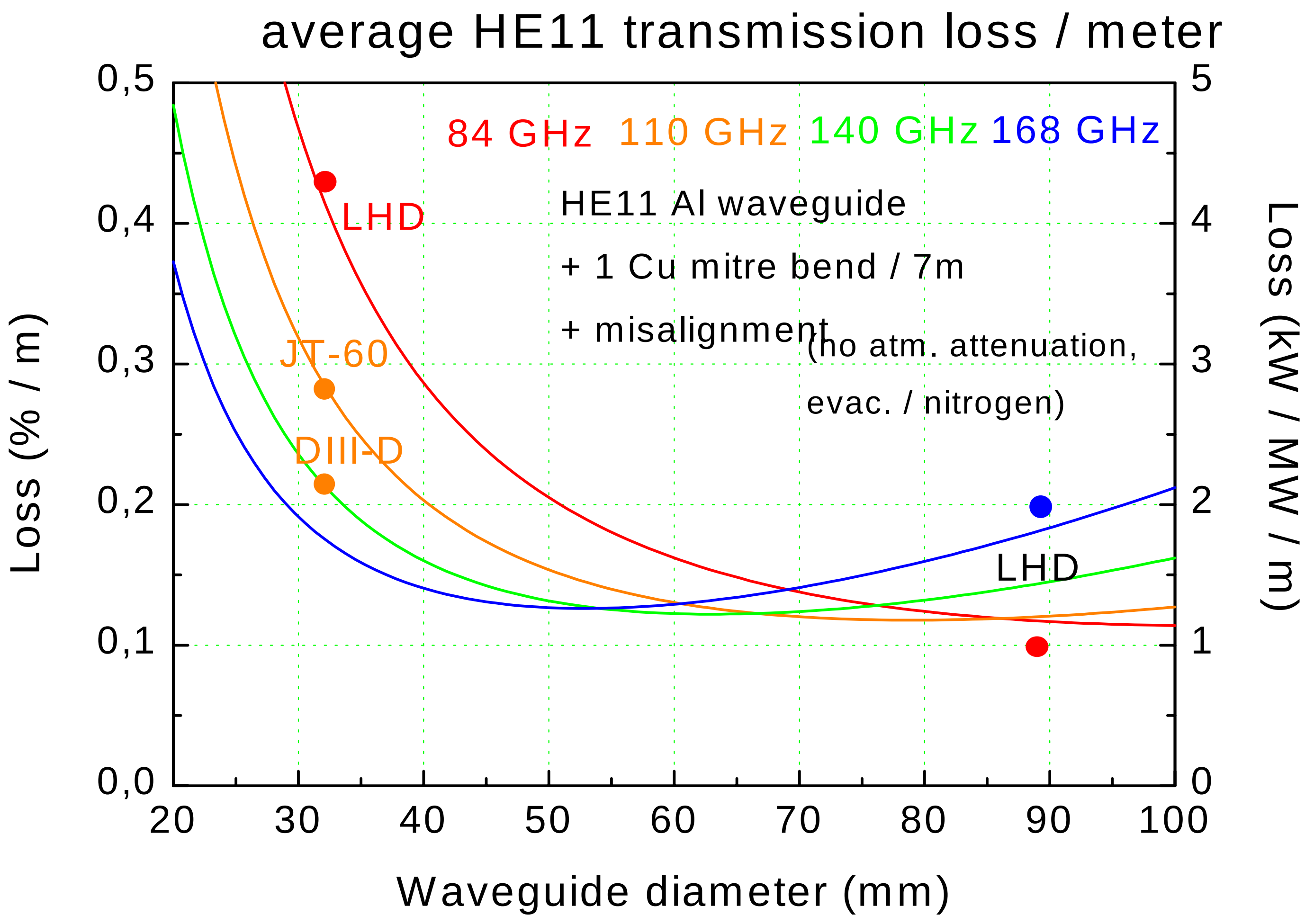
(H_20, O_2 around 60, 118 and 180 GHz)



Small diameter (low frequencies)**: Mitre bends and waveguides produce most of loss**

Large diameter (high frequencies)**: High-precision components + careful alignment required**

Optimization of waveguide diameter



Results of transmission lines agree well with theory (examples > 60 m)

For ITER, D = 63.5 mm gives nearly minimum loss and is compatible with 2 MW

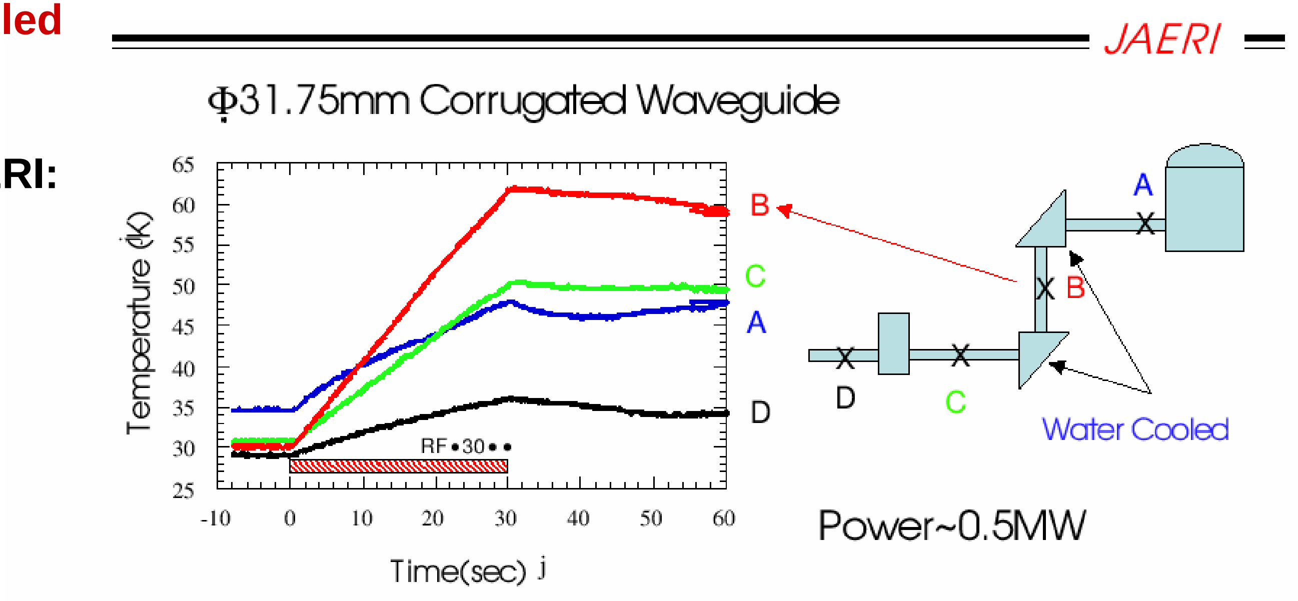
Mitre bends excite higher-order modes due to internal diffraction

==> main source of arcing in non-evacuated waveguides

==> high-order modes are **subsequently damped in waveguide**

==> waveguide must be cooled for CW-operation!

Experiment at JAERI:



==> use diffraction-reduced bends! ==> Improvement 2.....8

Phase corrected mirrors

Rippled wall HE11-HE12 partial mode converters (Doane and Moeller, 1994)

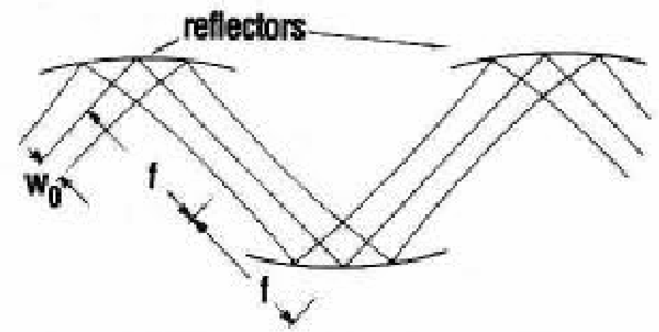
Mode-converting horn-mode type bends (IAP Nizhny Novgorod)

+ mode-filtering gaps + larger diameter +..... **Can water-cooling of waveguide be avoided?**

Test of the transmission line 82.7GHz /200kW /CW

$P_0 = 200$ kW , $\tau = 1000$ sec., $\eta_{tr.line} = 95\%$

Beam transmission



Propagation of gaussian beam

by iterative focussing with reflectors

$$E(x,y,z) \quad \propto \quad e^{-\frac{x^2+y^2}{w(z)^w}} \cdot e^{-ik\frac{x^2+y^2}{2R(z)}} \cdot e^{i\Theta(z)}$$

For higher order modes m,n:

diffraction increases with mode number ==> **mode filtering**

Phase factor $\theta_{mn}(z) = (1+m+n)\ \theta(z)$ ==> **imaging properties**

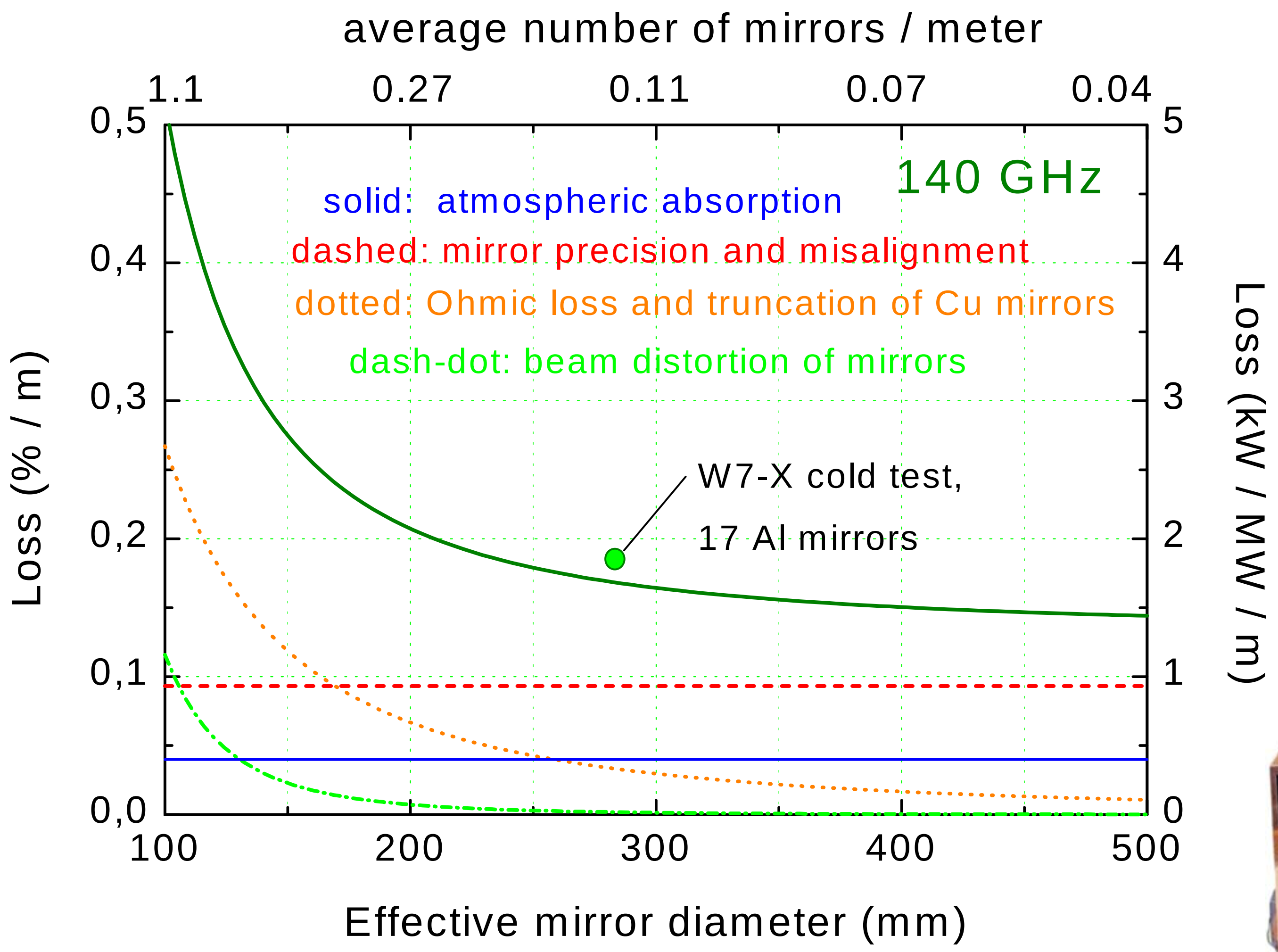
Curved mirrors lead to beam distortion ==> **mode conv. Loss**

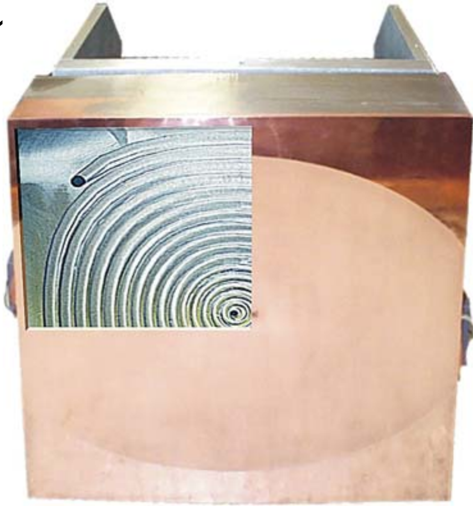
Imperfect mirror surface, truncation ==> **diffraction loss**

Transmission in air: ==> **atmospheric absorption**

(H_2O, O_2 around 60, 118 and 183 GHz)

Typical beam waveguide loss / meter



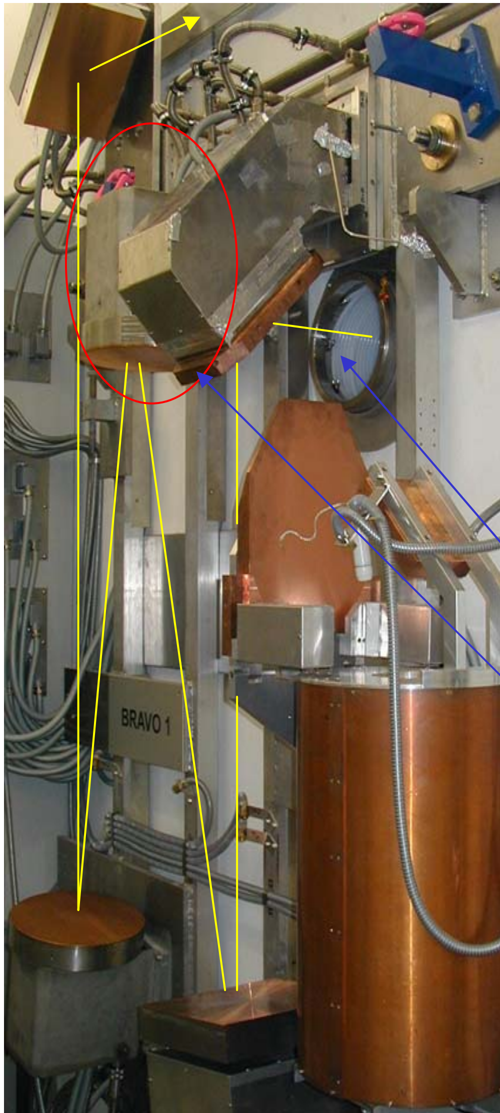


==> Beam diameter must be sufficiently large

==> High-quality components and alignment is essential

==> Air cooling, (+ drying or flushing with nitrogen) and stray radiation absorbers

W7-X optical transmission: Cooled components and installations



air cooling 200 KW

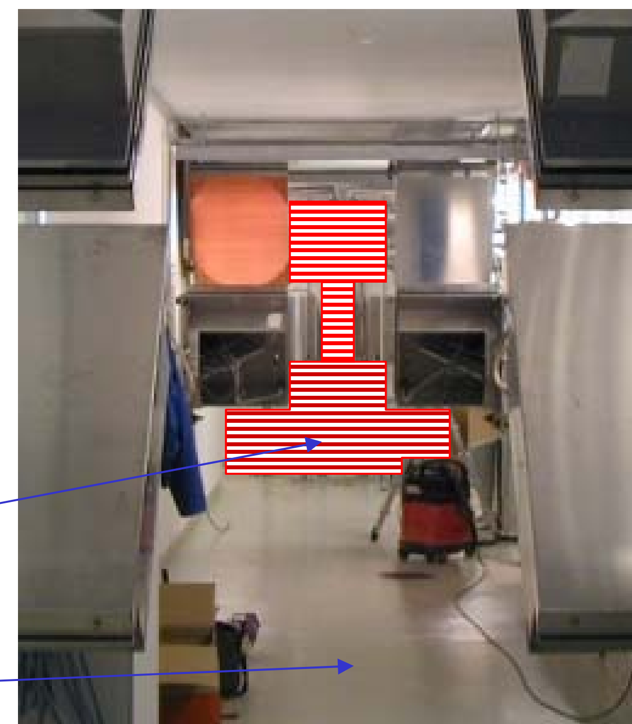
mirror cooling, ≤ 300 kW

absorbing tube (Teflon hoses) for gyrotron beam ≤300 kW

M1 stray radiation absorber (not installed), ≤ 200 kW

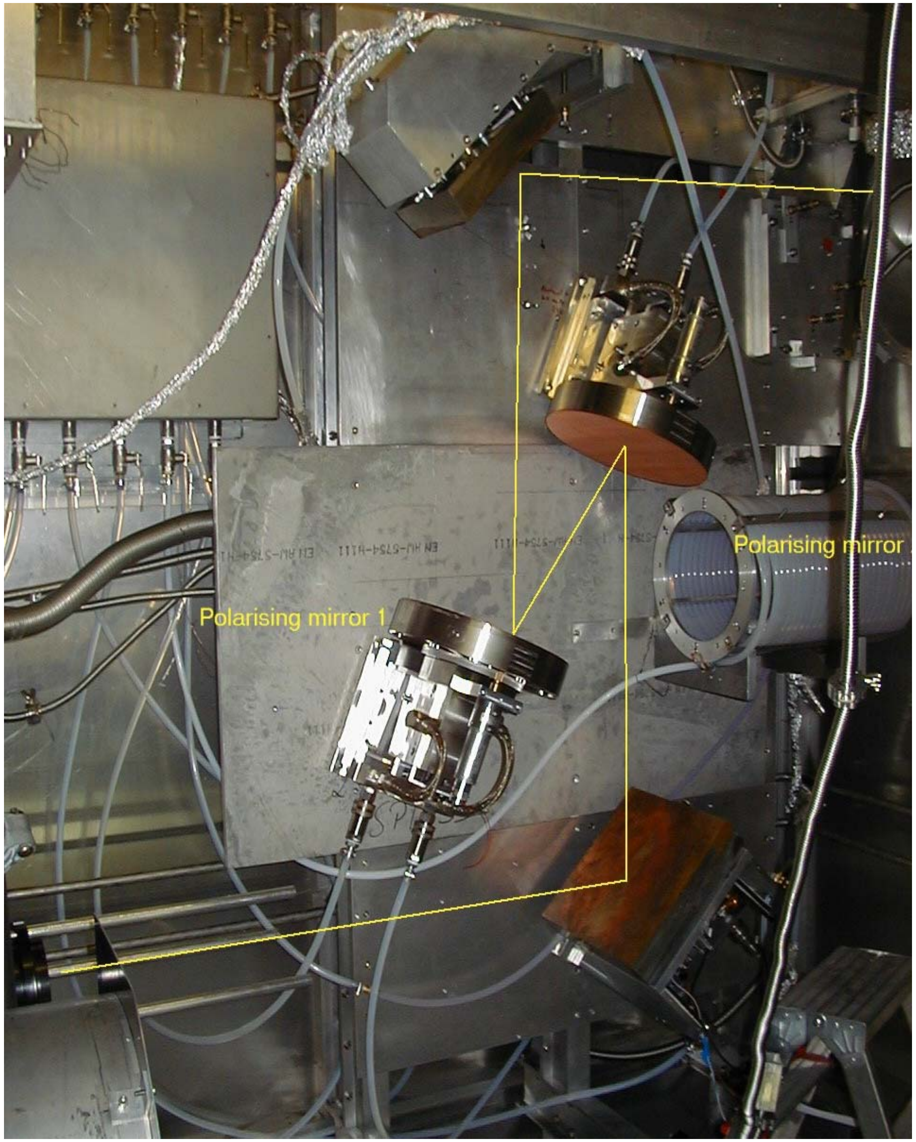
Actively cooled stray radiation absorbers, ≤ 300 kW

concret walls / floor to absorb remaining radiation, ≤ 200 kW



The W7-X Gyrotron test stand at FZK:

Test of mirrors, dummy load and rf-diagnostics with powers up to 890 kW / 180 sec



140 GHz gyrotron

Load (CCR)

Matching optics M1, M2:

no visible problems

Polarizers (sinusoidal corrugation):

no arcing, if polarizers are clean

==> increase of power capability of the dummy load)

directional coupler
using an integrated waveguide

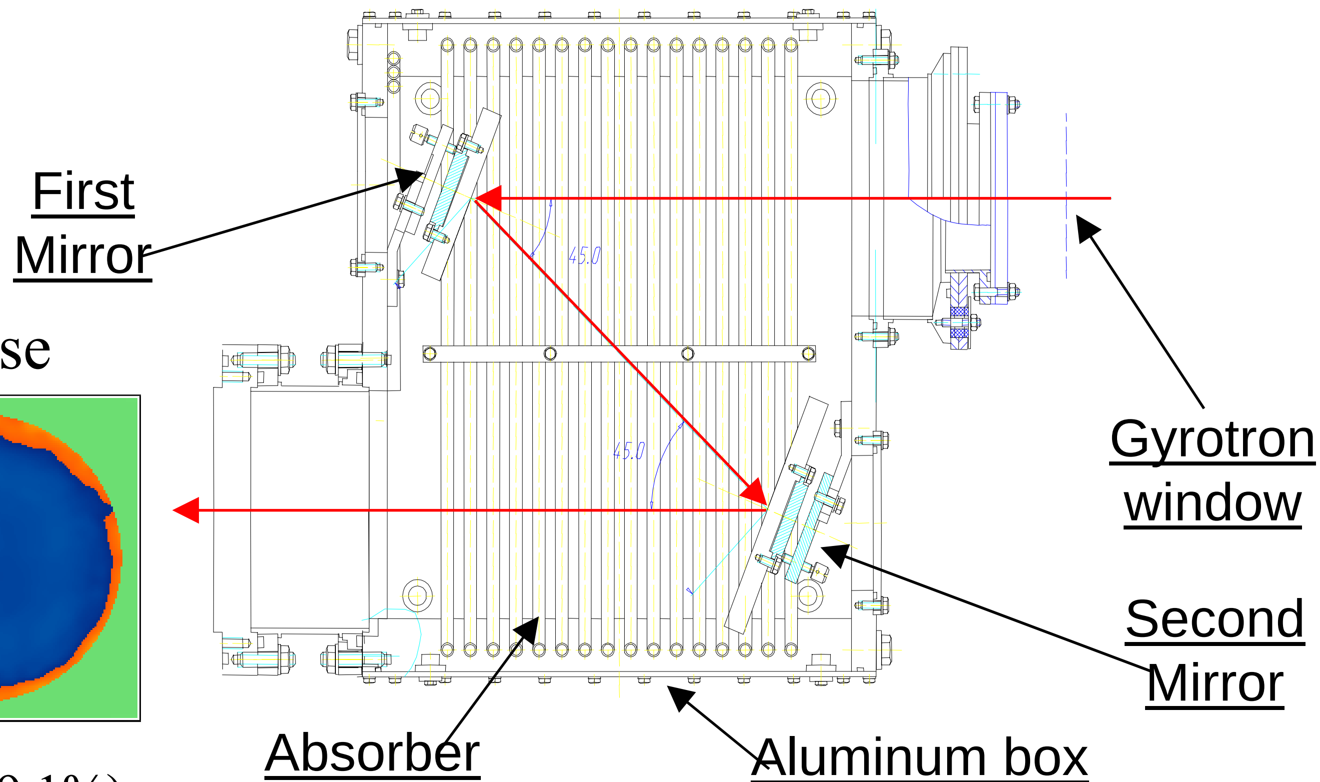
==> CW-compatible

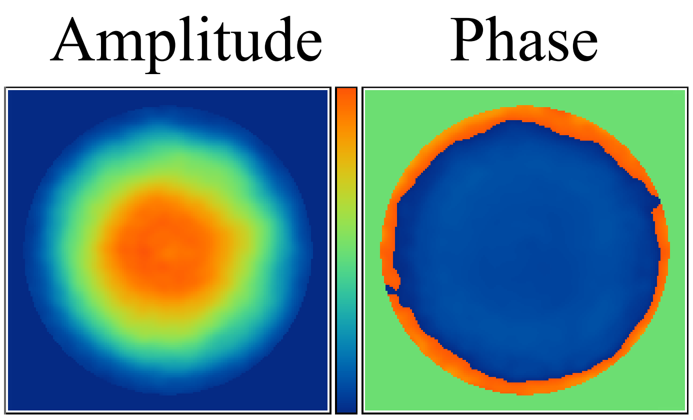
Matching of the gyrotron beam to the transmission line

Efficient methods available to transform gyrotron beam to HE11 or TEM00

Typical set-up: 2 phase-correcting mirrors

Institute of Applied Physics Academy of Sciences





$\eta_a(\eta_{a,ph})_{\text{HE11}} = 99.8\% \; (99.1\%)$

High quality of output beams reached, but:

- **High alignment accuracy needed**: for HE_{11}: ==> mode conversion
  for TEM_{00}: ==> misaligned gaussian beam
- **Alignment usually done with short pulse**

  ==> Long-term mechanical stability of internal mirrors and MOU mirrors

  ==> Frequency stability of gyrotron ==> varying output of beam ≤ 500 ms, **d/w_0=0.25**
- **Stray radiation from inside the gyrotron is not re-converted**

  ==> risk of enhanced reflection back to the gyrotron

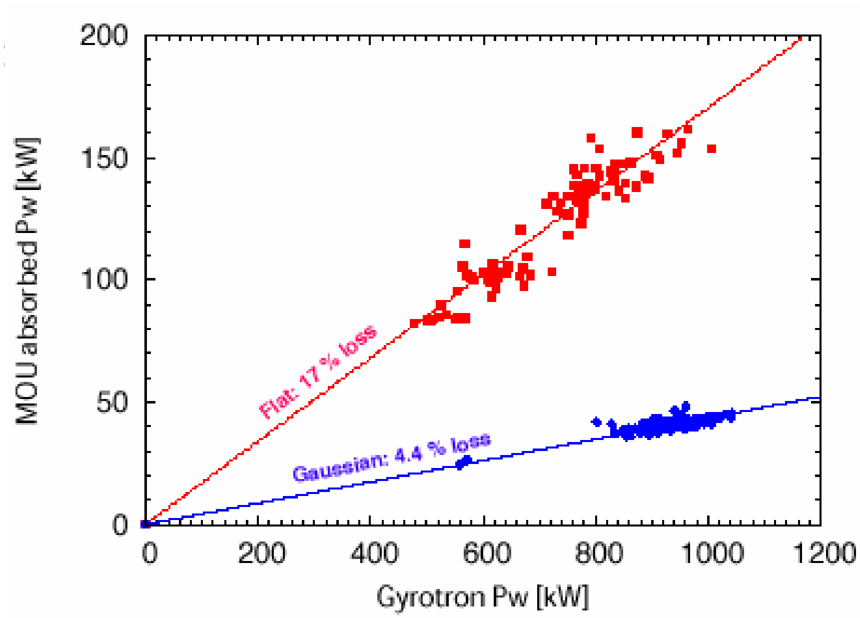
J. Lohr et al, GA San Diego:

comparison of MOU loss

gyrotrons with

ext. Phase correction

gaussian beam,
(single mirror MOU)



WANTED for CW:

Gyrotrons with

high beam quality and

low stray radiation

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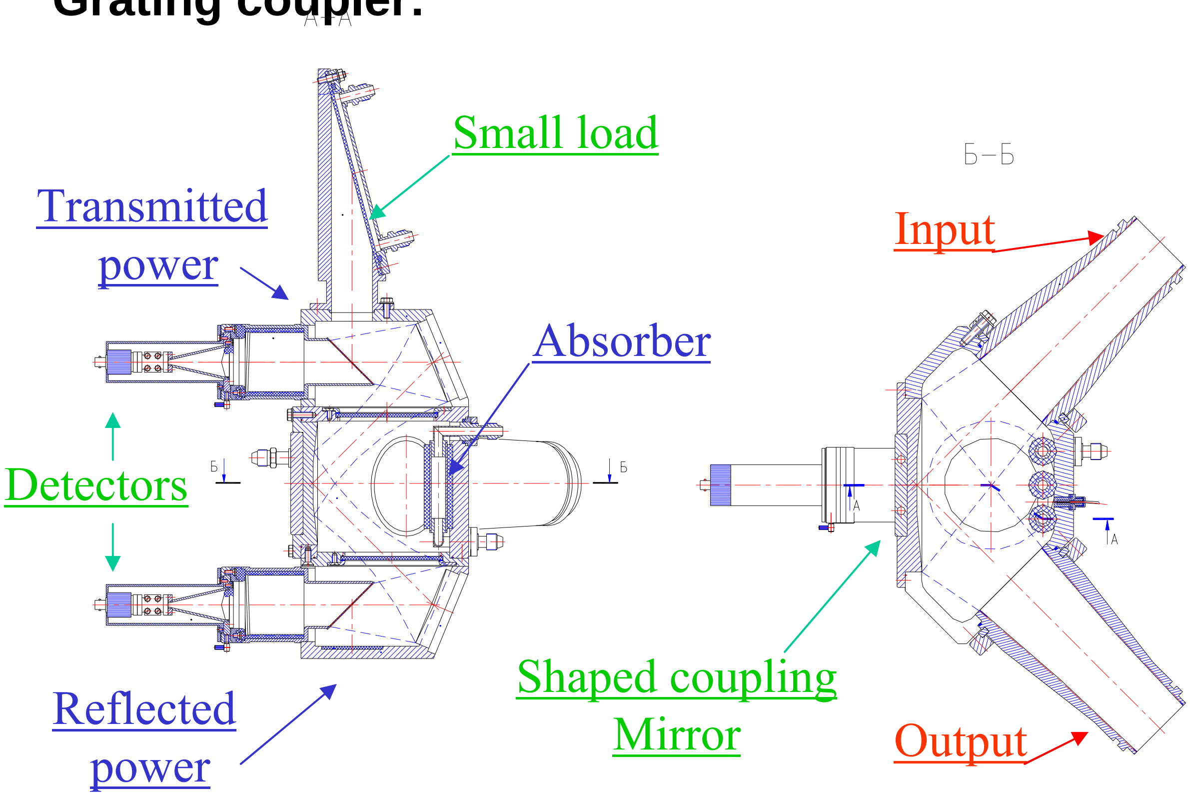
Meter of transmitted and reflected power in a quasi-optical miter bend

Grating coupler:

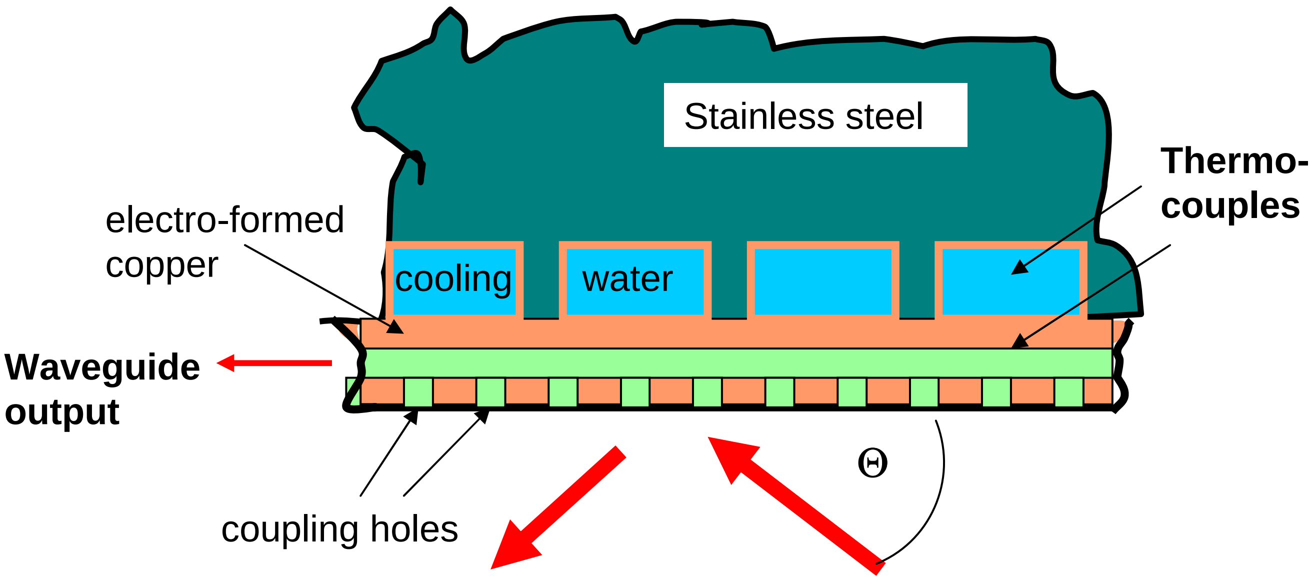


Measuring channels

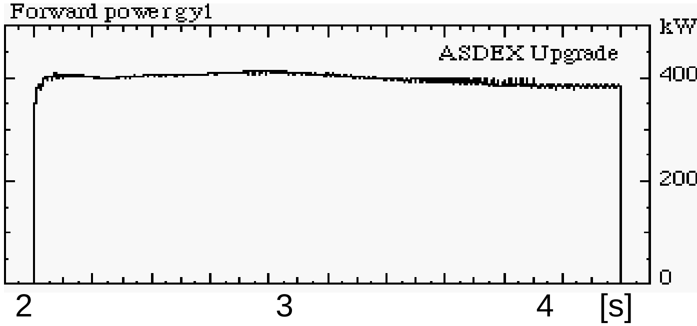
Main channel

Diffraction losses – 0.1%

Compact power monitors for water-cooled (mitre bend) mirrors



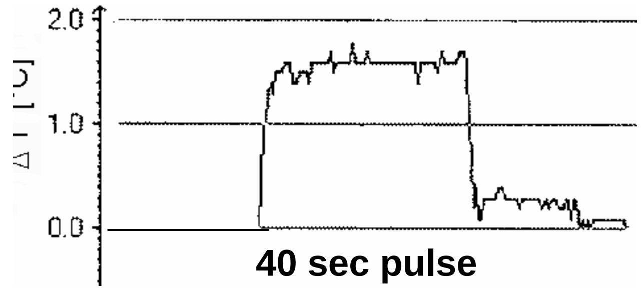
$$\cos\theta = \sqrt{(1-(\lambda/2a)^2)}$$



waveguide coupler:

coupling of radiation to monomode waveguide,

RF measurement



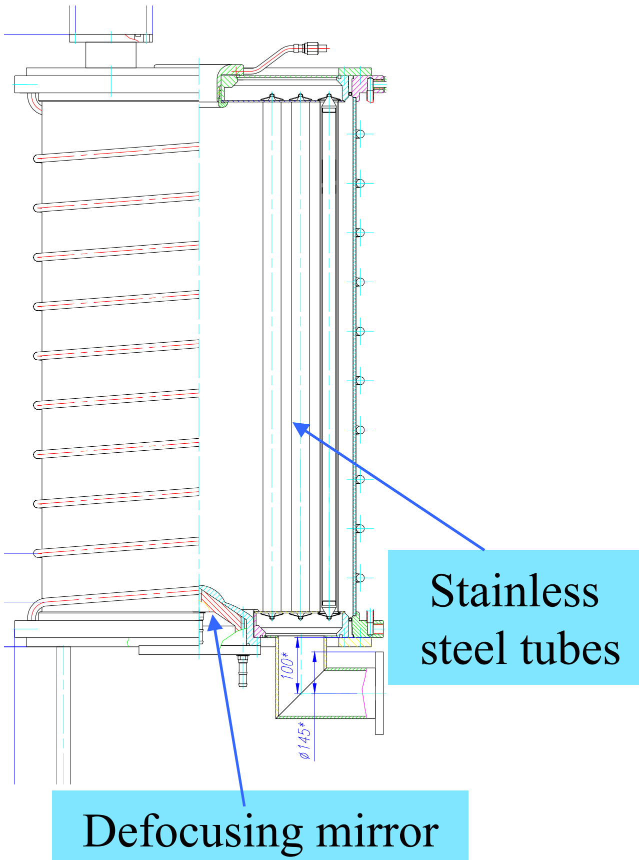
Thermocouples:

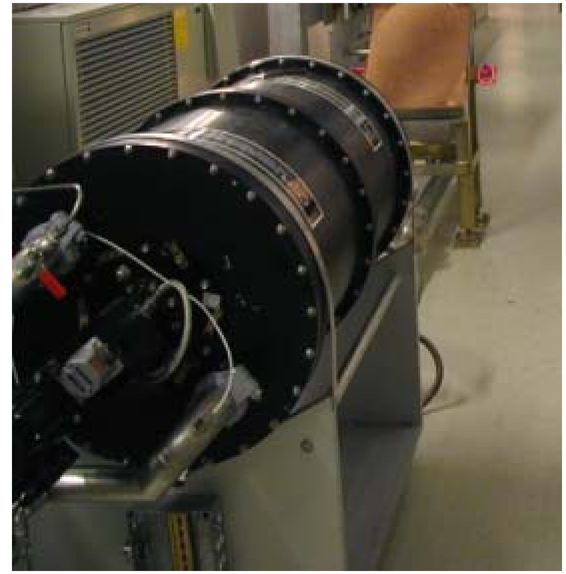
calorimetric power measurement: P ∝ T(outlet) - T(inlet),

P ∝ T(copper) - T(water)

Calorimetric loads, designed for 1 MW CW:

IAP N. Novgorod:





Calabazas Creek Research:

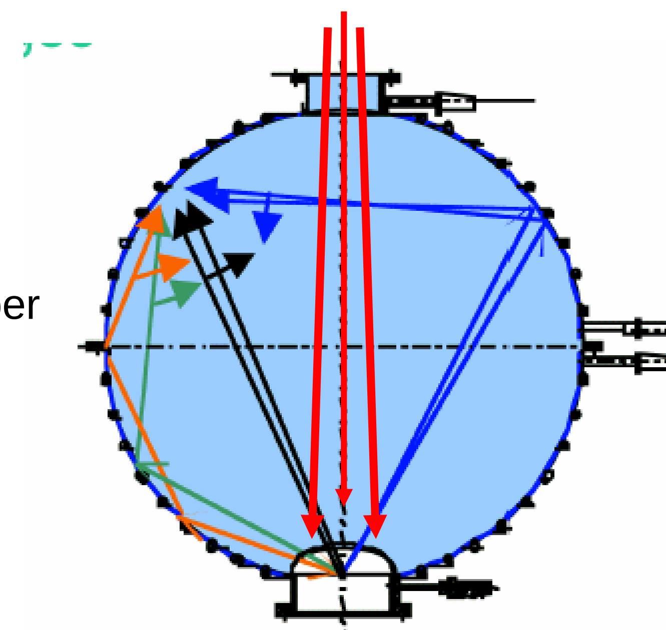
rotating mirror

TiO_2 -absorber

IFP Milano:

spherical load

CrO_2 - absorber

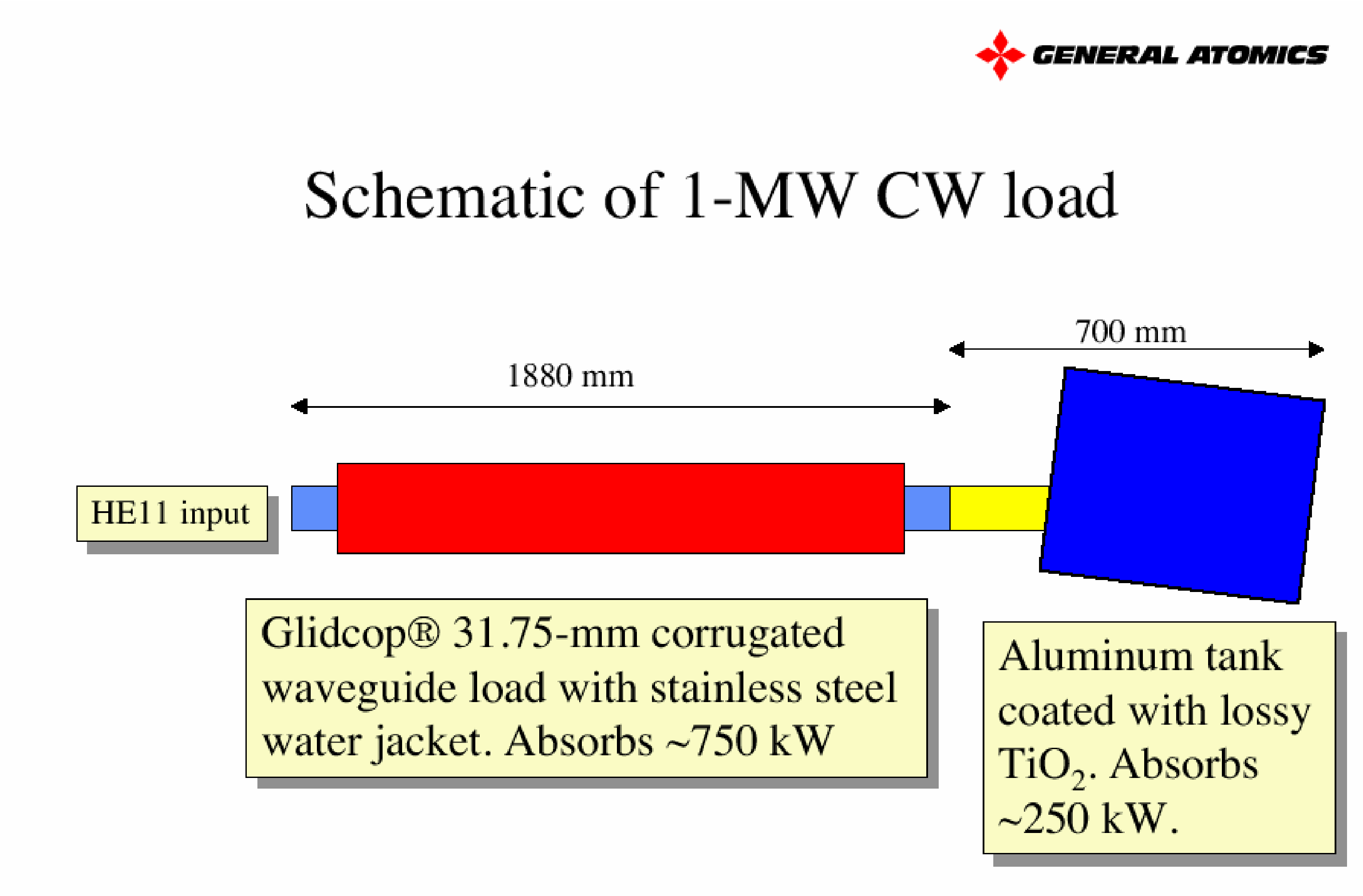


Typical problems: - **reflection of a few percent**

- **quality of coating (CCR)**

==> Loads must often be used with a pre-load

==> Alternative solution: waveguide with strong attenuation followed by load



Launchers for CW ECRH / ECCD

Requirements

- **poloidal and toroidal beam steering**
- **fast steering to follow NTMs**
- **high reliability**

Examples:

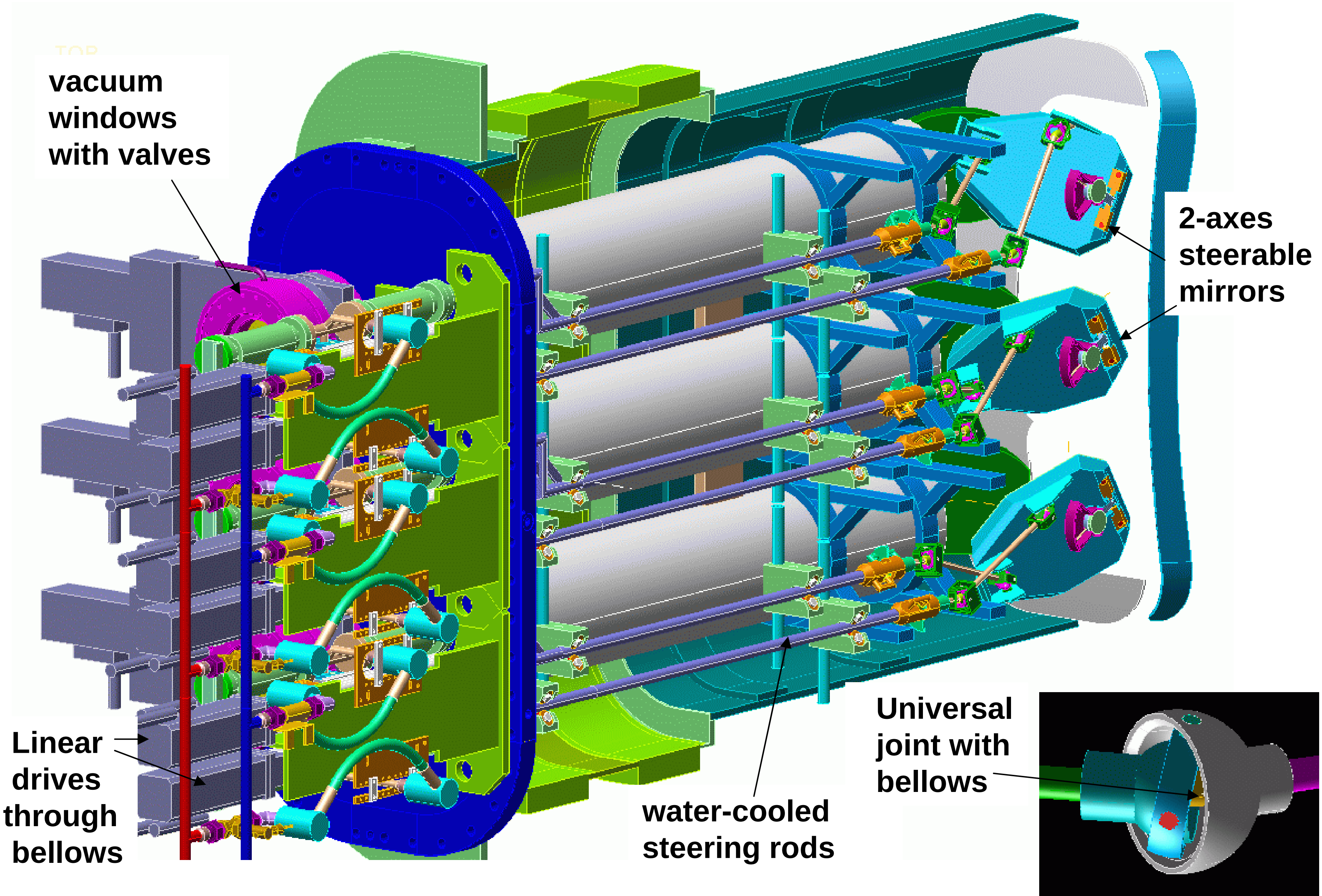
- **fast movable launchers on DIII-D, JT-60 and ASDEX-Ug,**

  ITER Upper Launcher ==> talks this conference

- **W7-X plug-in launchers**
- **ITER mid-plane launcher**
- **Tore Supra**

W7-X plug-in launcher:

4 launchers with 3 individual antennas each



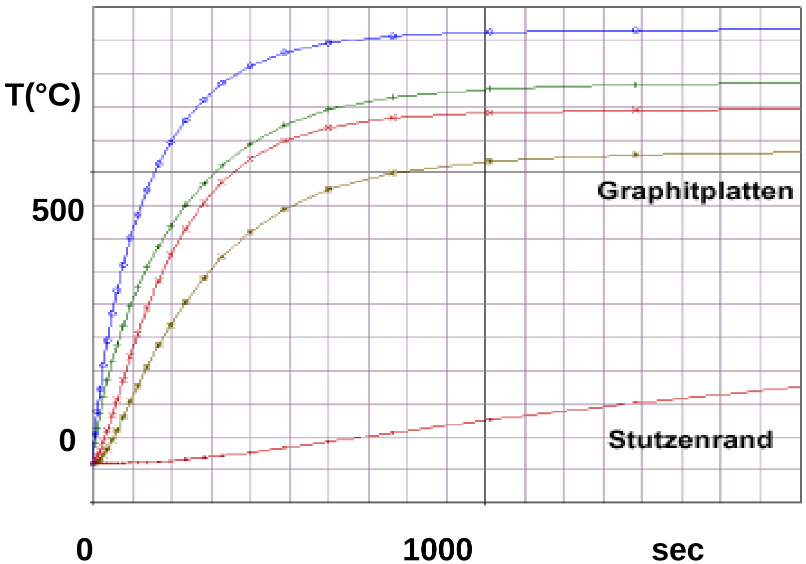
Heat loads in W7-X launchers

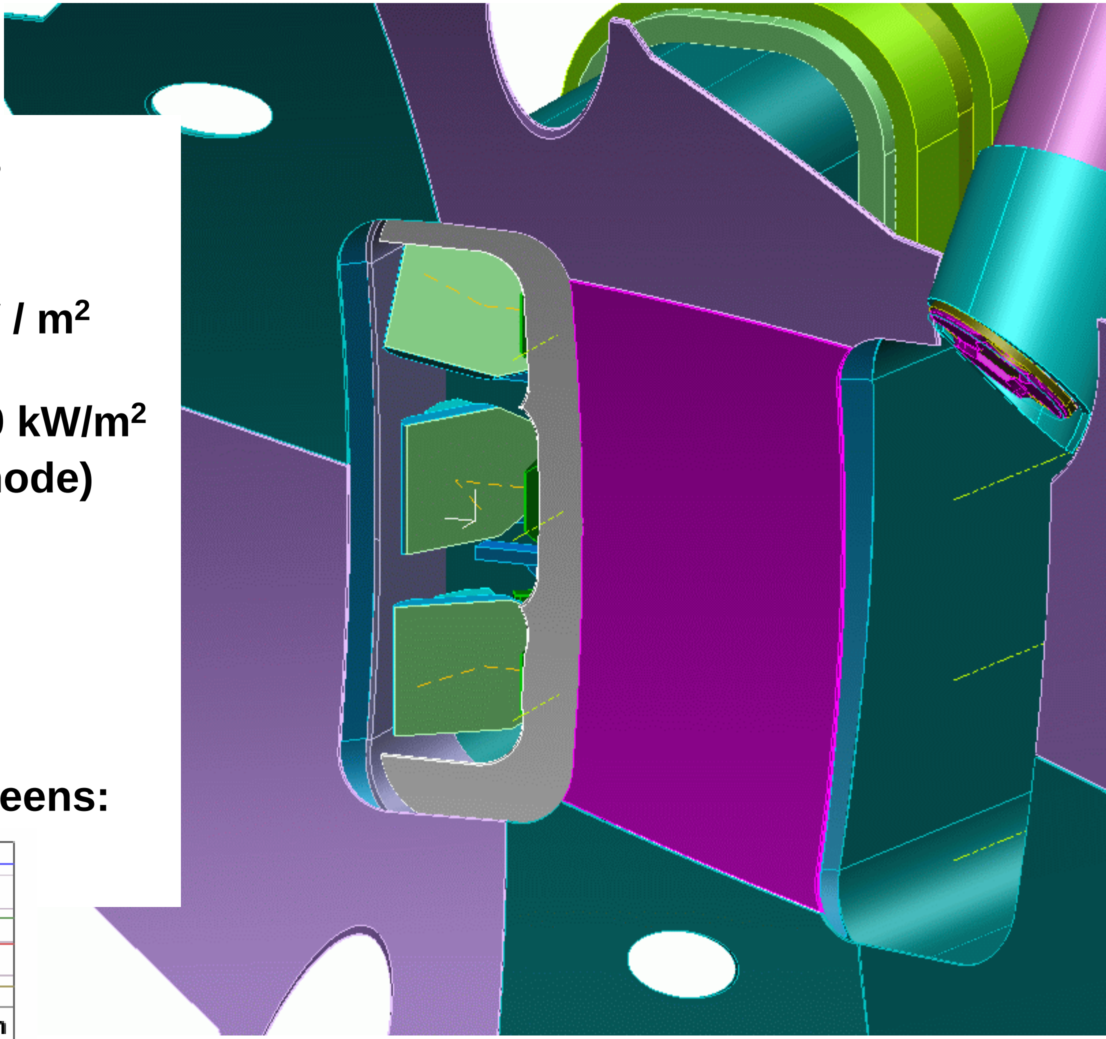
Plasma radiation: < 100 kW / m^2

Diffuse mm-wave radiation: 10.....200 kW/m^2
(low for X2-mode, high for O2-mode)

In-vessel mirrors:
thermal loads depending on design

Temperature on radiation-cooled screens:





Equatorial EC Launcher

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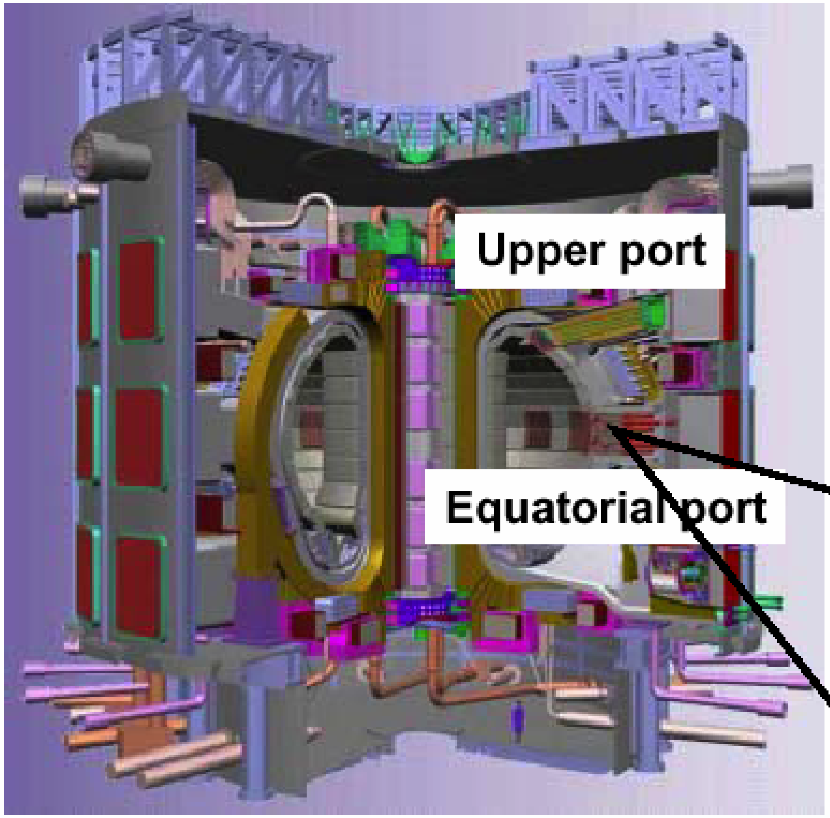
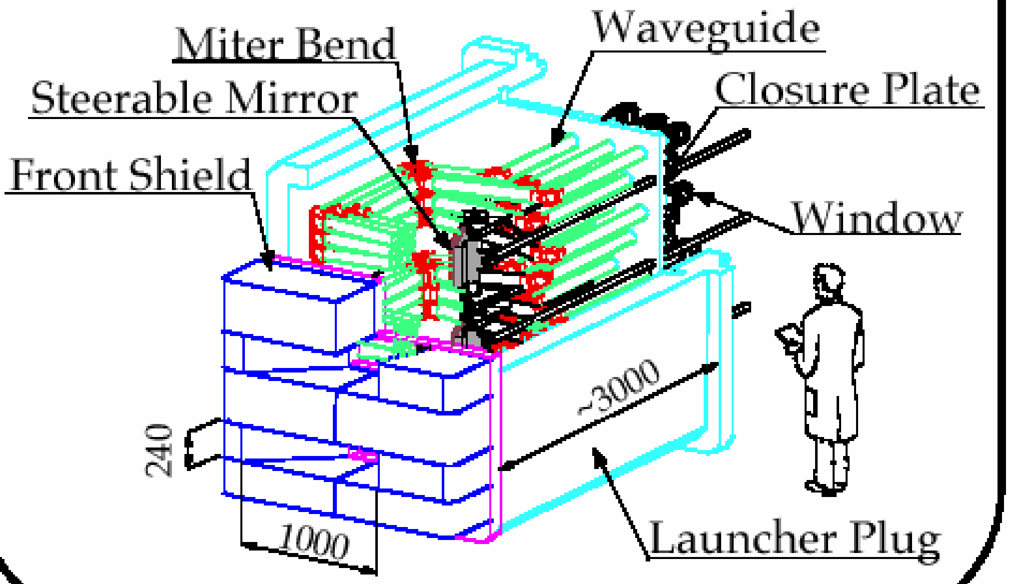
ITER 3D view



Launcher 3D view

Front shield : Based on ITER blanket
Plug : Mirrors, Waveguides, N-shields, Drive mech., etc…



Mechanical tests of a flexible cooling tube

JAERI

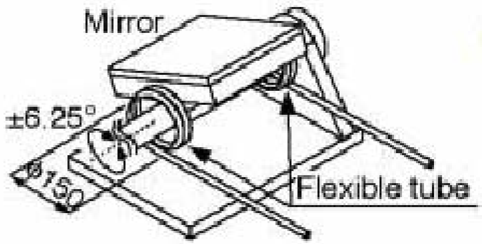
Analysis model

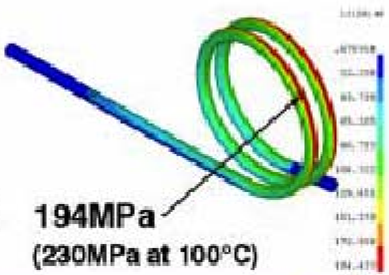
Tube : $\phi_{in/out}$=10/12, SS316

Rot. θ : ±6.5°

Internal pressure: 2MPa

Result





- Life time of the tube would be 3×10^4 cycles considering the fatigue data*(cycles to failure at 200MPa loading : ~10^5) and the safety factor of 1/3.

*A. Baumel Jr. and T. Seeger, "Material Data for Cyclic Loading", 61, Suppl. 1 (1990), Elsevier Science. Co.

Fatigue tests (on-going)

Tube : Same as design

Rot. θ : ±6.5°

Rot. vel. : 1.3 °/sec

Internal pressure : 2MPa

So far, 2.0×10^4 cycles are succeeded.

Flexible tube

Bearings (WC alloys)

Steering mirror (Design and analysis model)

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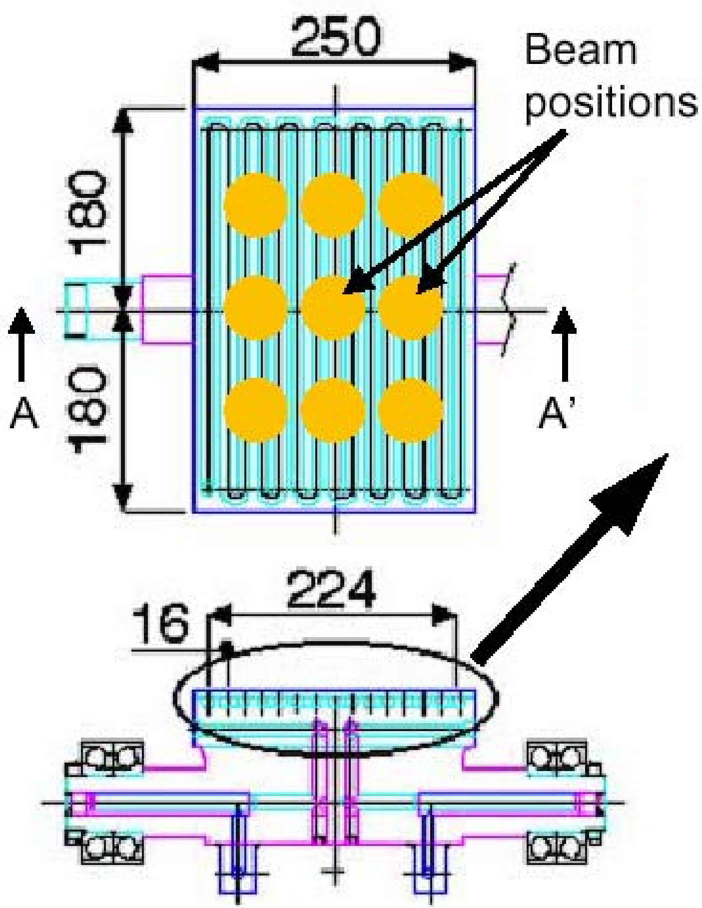
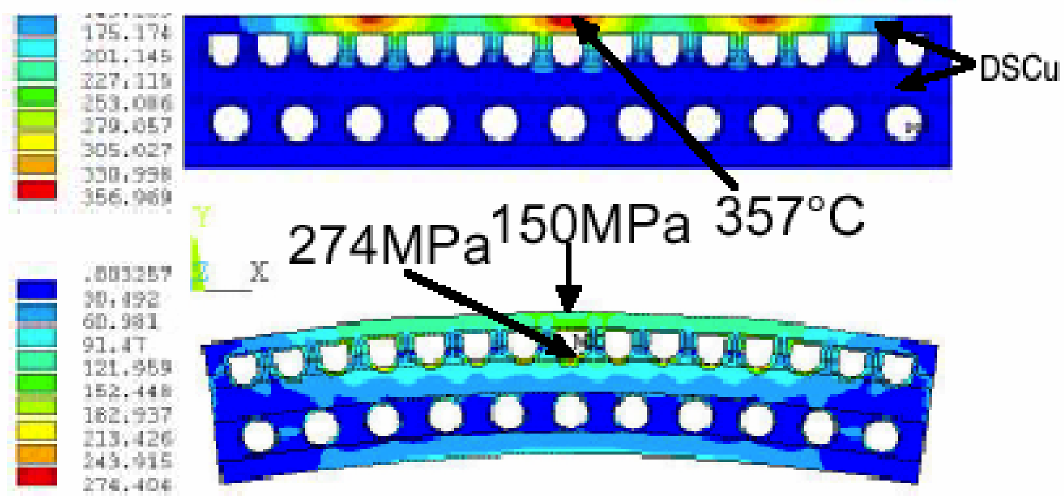


Mirror design



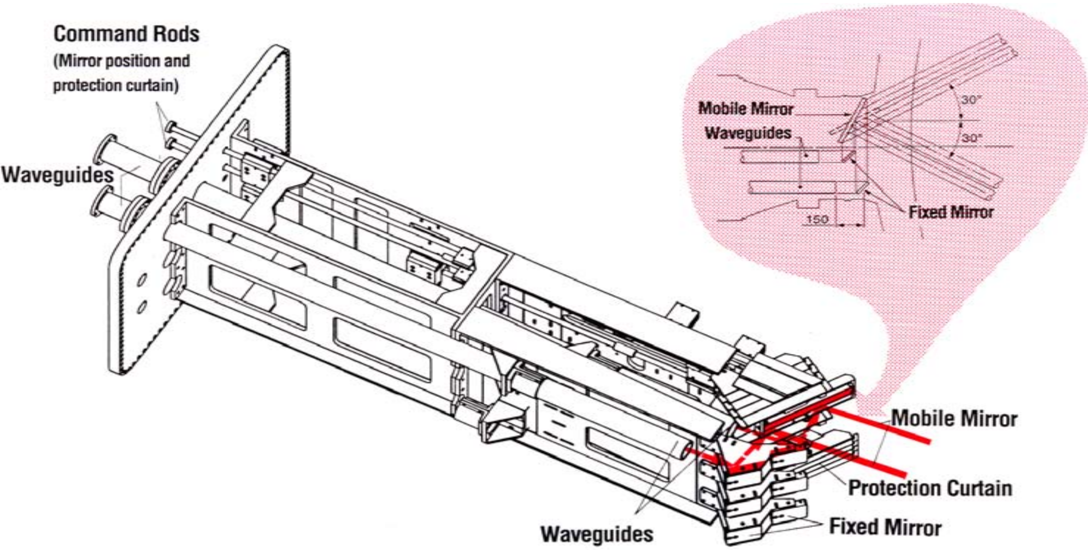
Flow velocity : 2m/sec

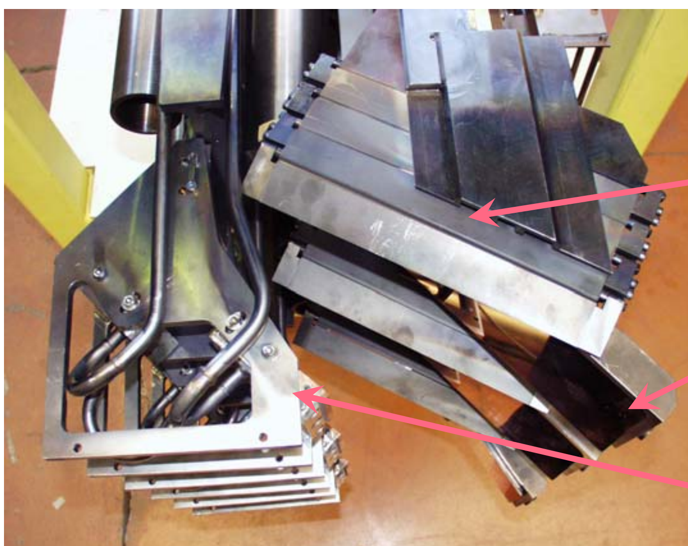
Calculation condition

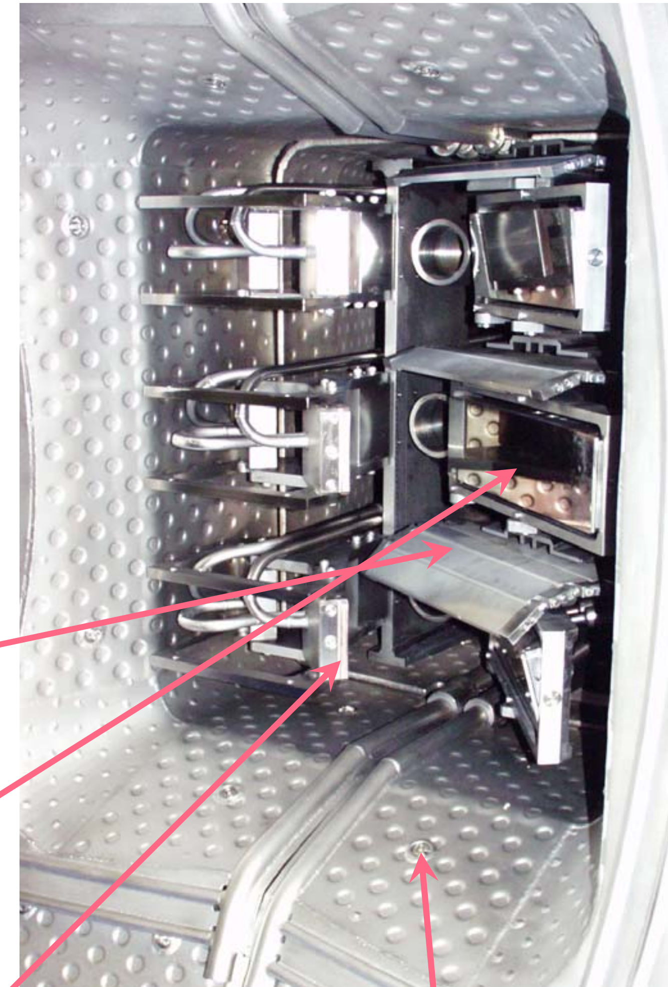
- Ave. Heat flux: $0.2 MW/m^2$
- Nuclear heating : $1.0 MW/m^3$
- RF heat load(peak) : $3.1 MW/m^2$
- RF distribution : Gaussian

The Tore Supra Antenna System

CEA Cadarache







Retractable Protection

3 Mobile Mirror

6 Fixed Mirror

Thermal port protection

Summary

- **CW lines:** minimization of loss for all components !

  Probably each component needs cooling

- **Launchers:** high reliability required,

  careful engineering of critical components necessary