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Feasibility of an ECRH system for JET: Options for an ECRH/ECCD launcher design

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Istituto di Fisica del Plasma "Piero Caldirola"

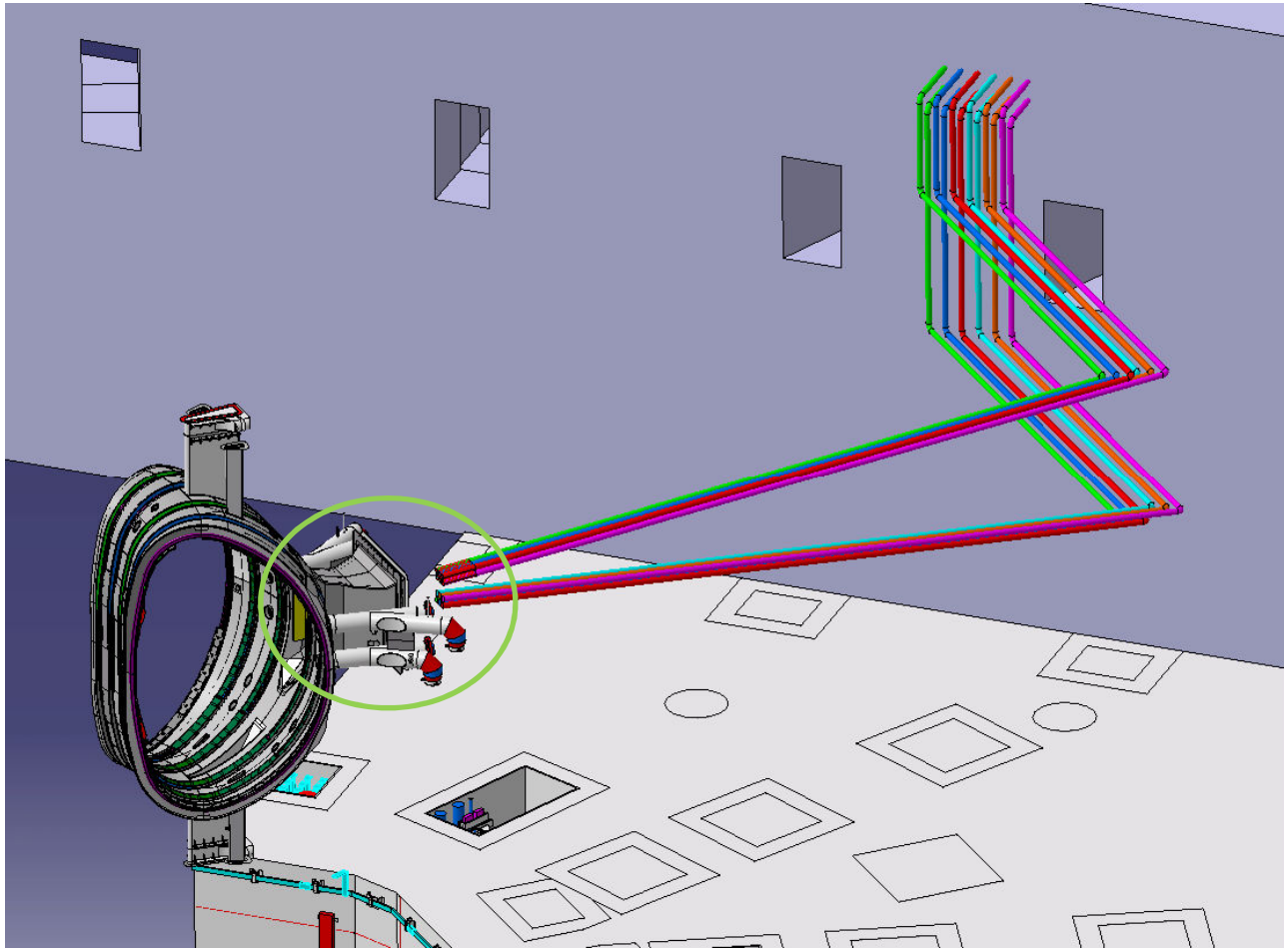
NTM and sawteeth control, core heating and current drive, current profile tailoring

- Study conducted to evaluate the feasibility of an ECRH system on the JET tokamak for the physics applications above. The possible options for the launcher have been investigated, assuming:
- a frequency of 170 GHz,
- use of an evacuated transmission line
- availability of an entire JET mid-plane port for the launching system.

- FEASIBLE? YES,….

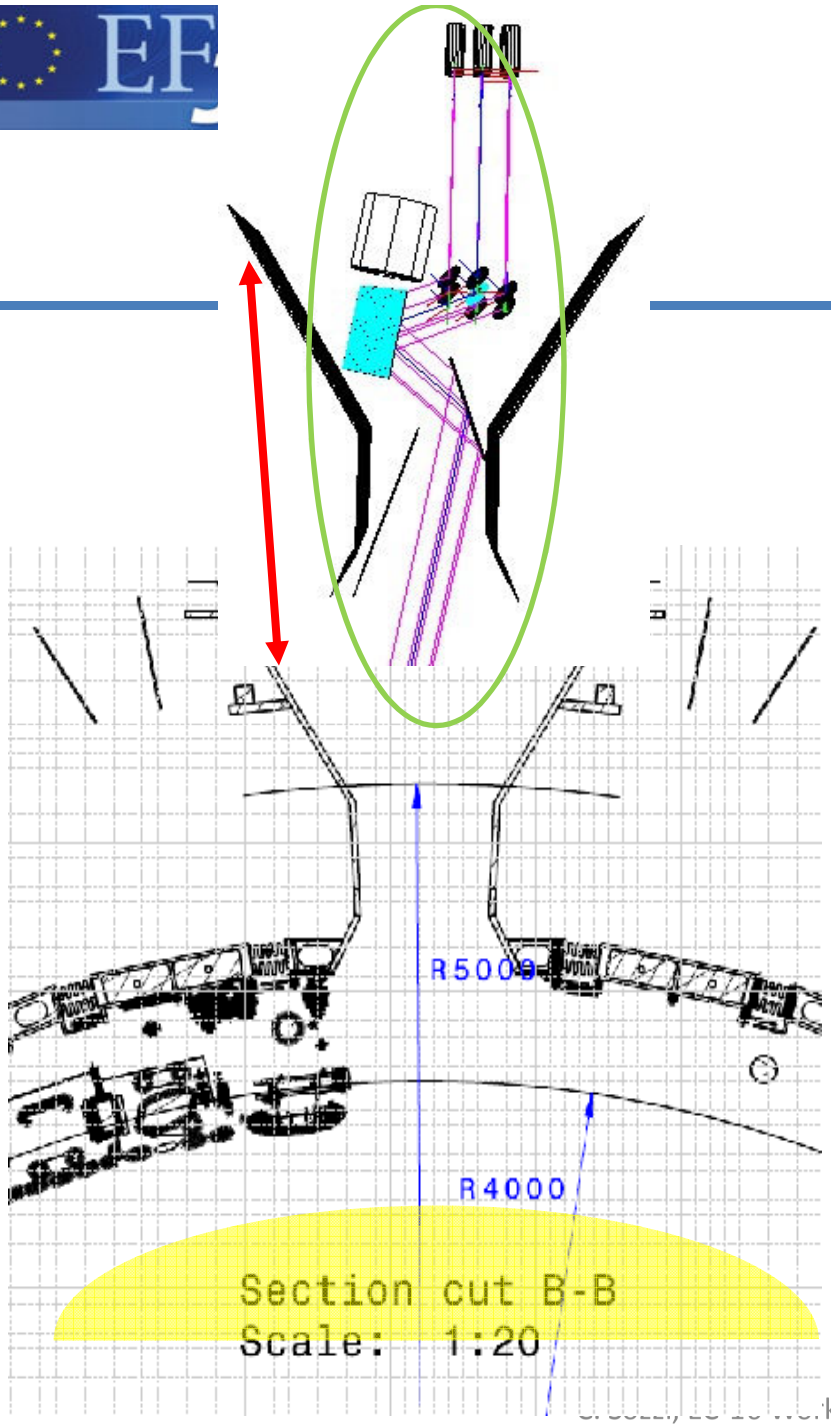
- The most powerful system wordlwide in an already existing (and rather crowded) machine!!!
- “Full scope” system: poloidal and toroidal steering, real time capabilities, tritium-grade integration
- Technology benchmark: test of the ITER steering system

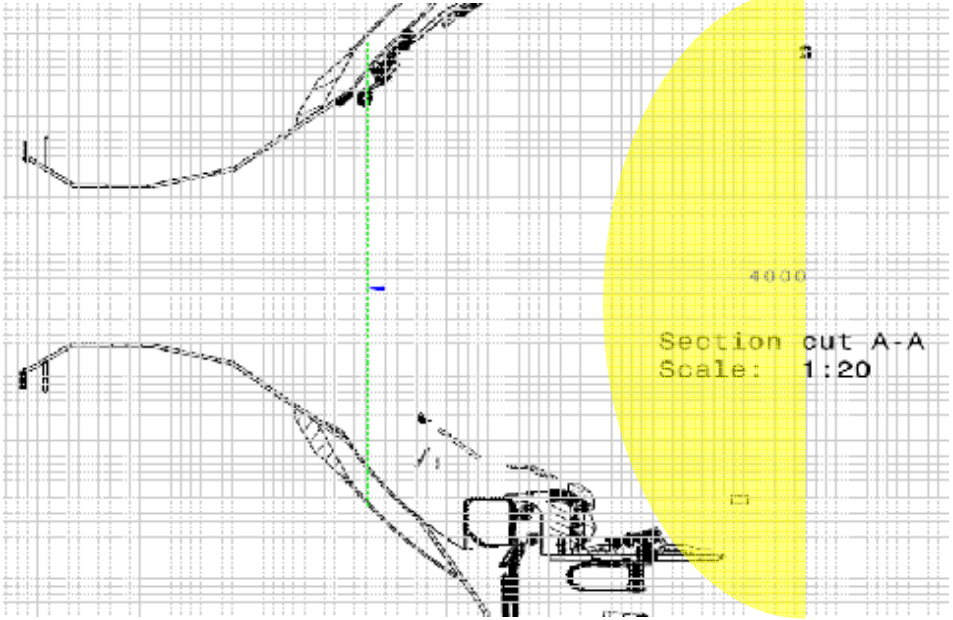
The JET port



- Access from port 2 (ILA antenna)
- 2 groups of waveguides feeding
- 2 steering units
- 6 beams each

The JET port: dimensions

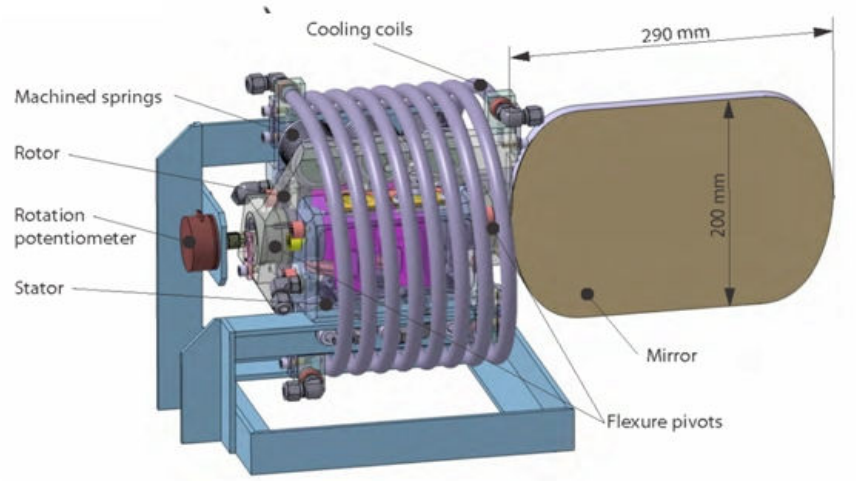


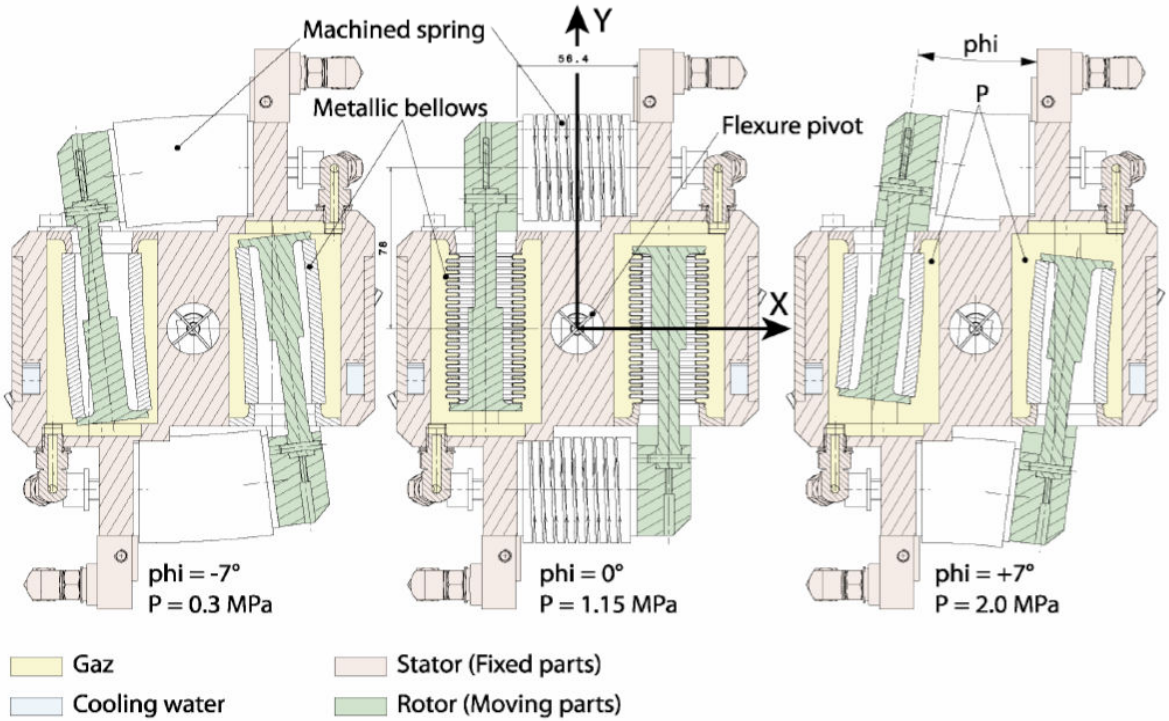


Main dimensions [mm] of the JET port and position with respect to major radius R:

section	Vertical	Horizontal
Port opening	1311	1383
Clearance (narrowest point)	960	452
Length	1030	1200
R at opening	5653	
R at limiter (eq. plane)	4200	
R at vessel centre	2996	

The ITER steering mechanism

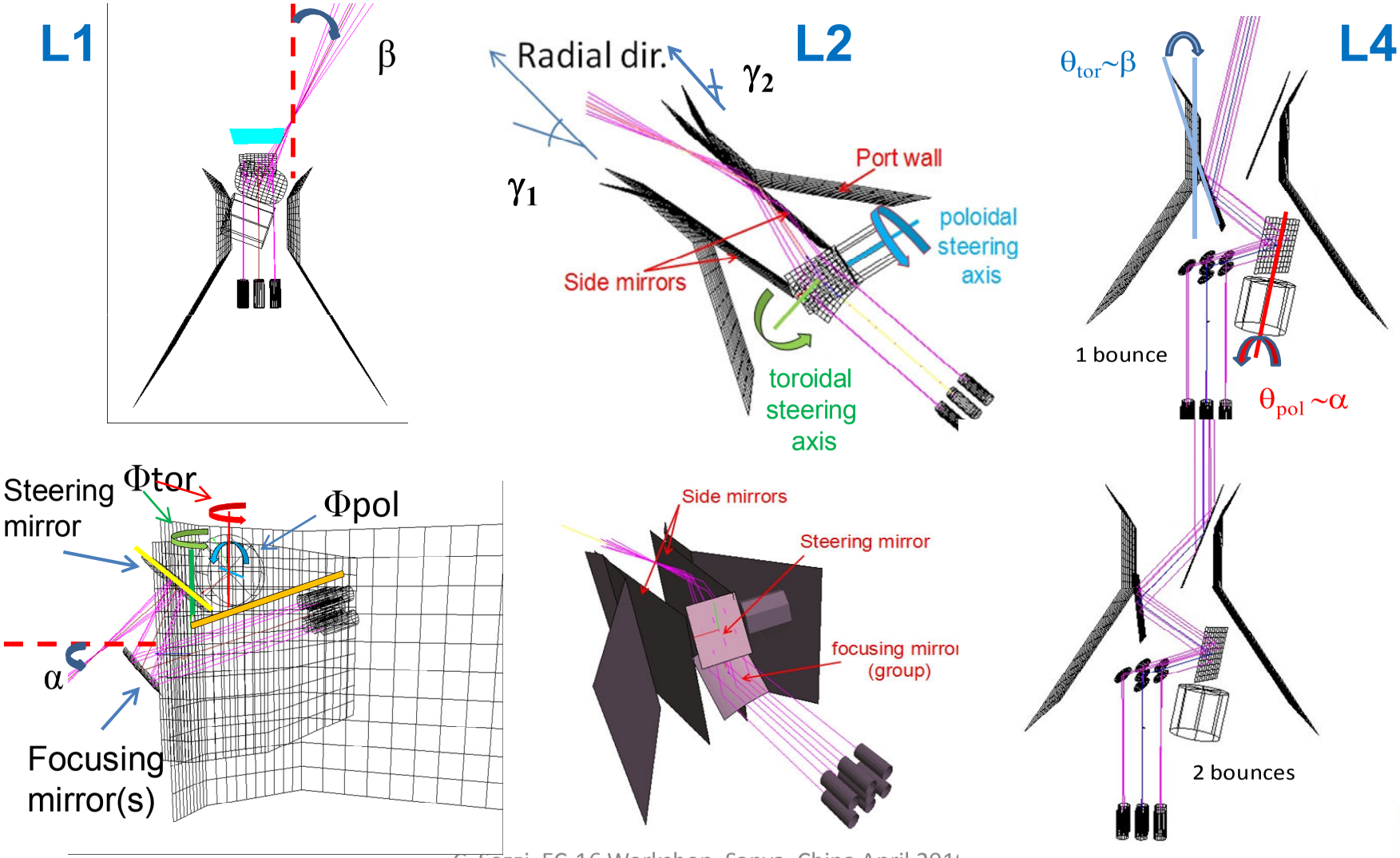




- Size: ~250(L)x245(D)mm
- Pneumatically activated
- Servo-valve controlled 3.5 to 21.5 bar
- Frictionless, no backlash
- Steering range: +/- 7°
- Full SM rotation in less than 3 secs
- 0.05° rotation accuracy

Developed at CRPP for F4E/ITER

Options


L1
β
L2
Radial dir.
γ2
γ1
Port wall
poloidal steering axis
Side mirrors
toroidal steering axis
L4
θtor~β
1 bounce
θpol ~α
Steering mirror
Φtor
Φpol
α
Focusing mirror(s)
Side mirrors
Steering mirror
focusing mirror (group)
2 bounces

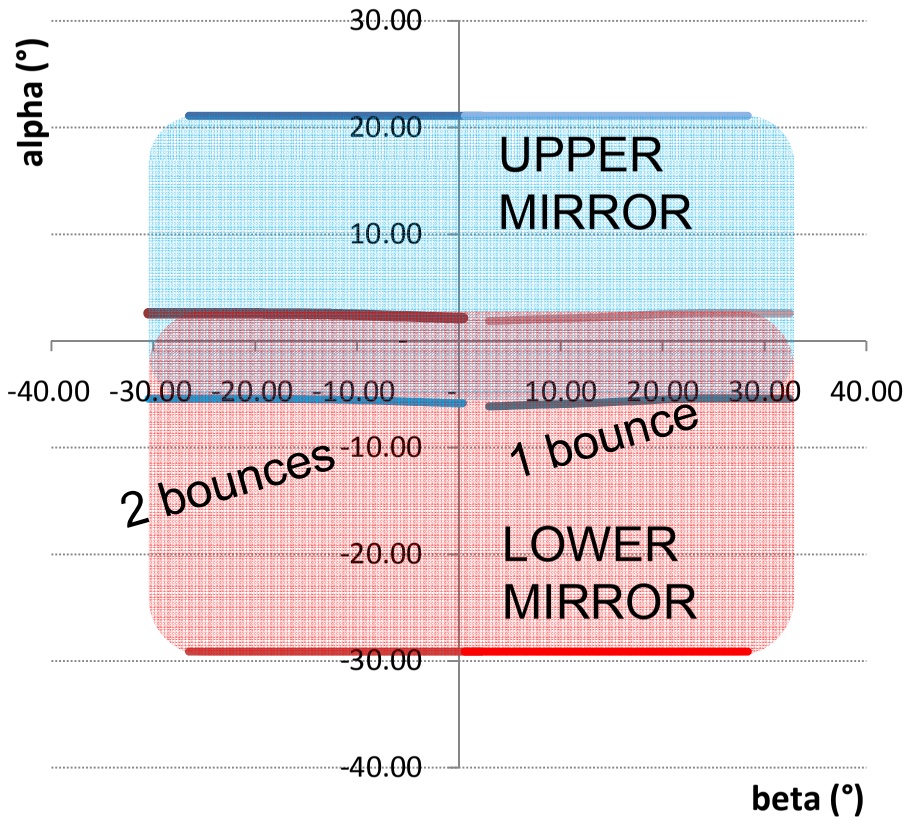
Basic technical requirements taken into account in the study and obtained performance (L4)

- ✓ Required steering range met (without significant gaps): toroidal range ± 30°, poloidal ± 25° (this last with real time capabilities)
- ✓ Power capability of 10 MW delivered into plasma (corresponding to 12 beams-12 waveguides as input to the launcher)
- ✓ Good optical performance (focusing and superposition)
- ✓ No modification of the ITER poloidal mechanism
- ✓ Poloidal and toroidal movements independent
- ✓ Toroidal mechanism could use same technology of poloidal (pneumatically activated) or push-pull bars (shot to shot positioning required)
- ✓ Port integration ok (room available, layout compatible for plug-in installation)
- ✓ Favorable situation for e.m. stress (large reflecting surfaces far from plasma or with minimum poloidal projection)
- ✓ Installation of a port extension or/and mode converter for optimal beam size is recommended

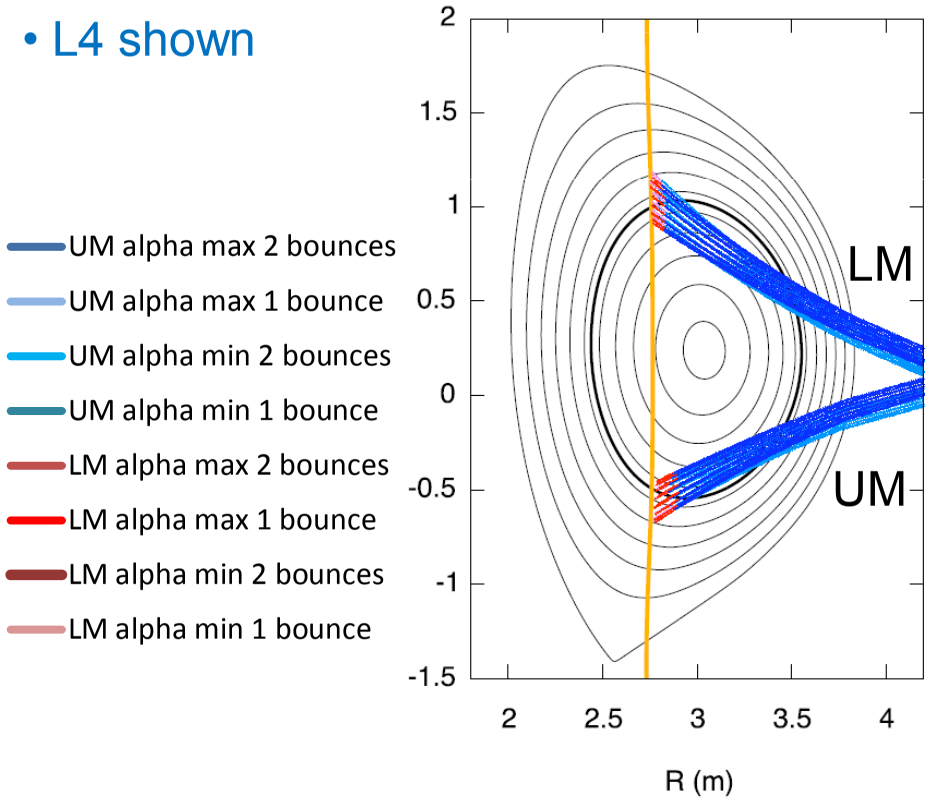
Steering range

Poloidal steering angle α: the angle between the horizontal plane (constant Z) and the poloidal component of the beam

Toroidal steering angle β: the angle between the beam and the poloidal plane

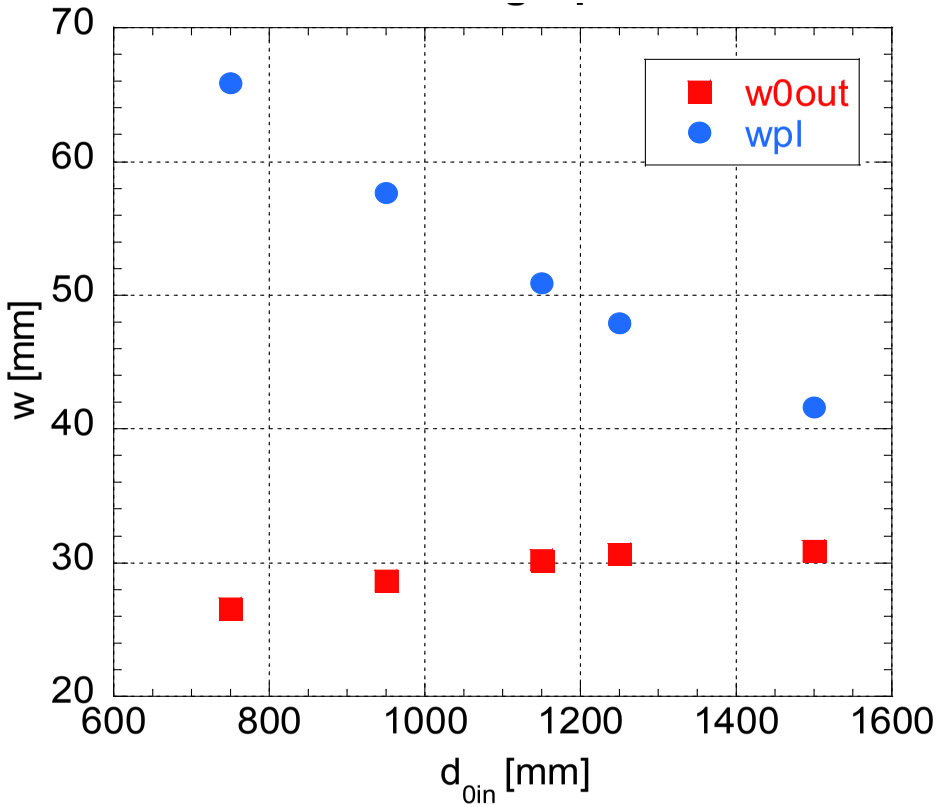


- L4 shown



Focusing optics and beam size optimization

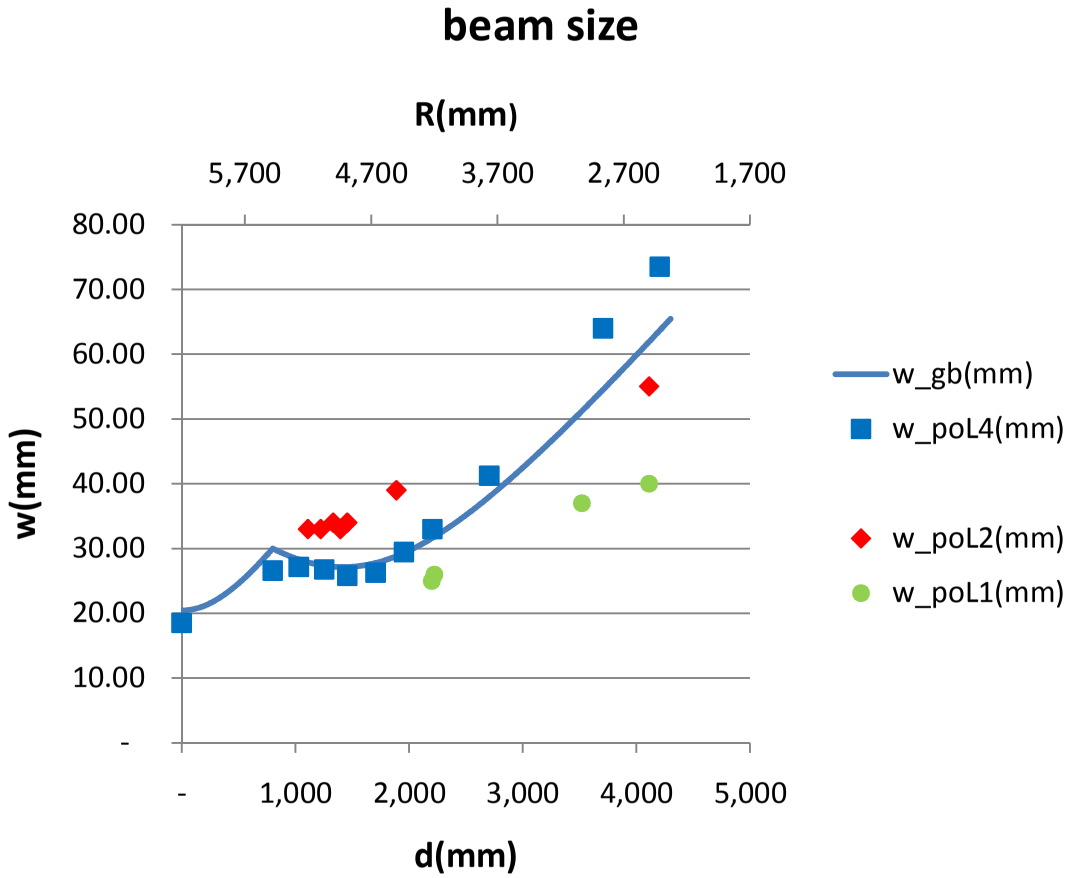
w0out (output beam waist) and wpl (beam size) at R=2500 mm)



As expected, larger input distance d0in gives better focusing in the plasma , with little effect on w0out .

- All launcher options use one focusing mirror (ellipsoidal surface) for each beam
- Input parameters: w0in (input beam waist = 20.4 mm at WG's tip) and d0in (input distance from the waveguide to the focusing mirror)
- Optimization criterion: minimize beam dimension in the plasma.
- Output parameters: focal length f of the mirror, ellipsoidal surface equation and location

Beam size (radius of the circle containing the $1/e^2$ =-8.7dB contour with respect to the peak intensity) computed with PO GRASP code for the central ray of the upper launching system, in radial propagation direction.

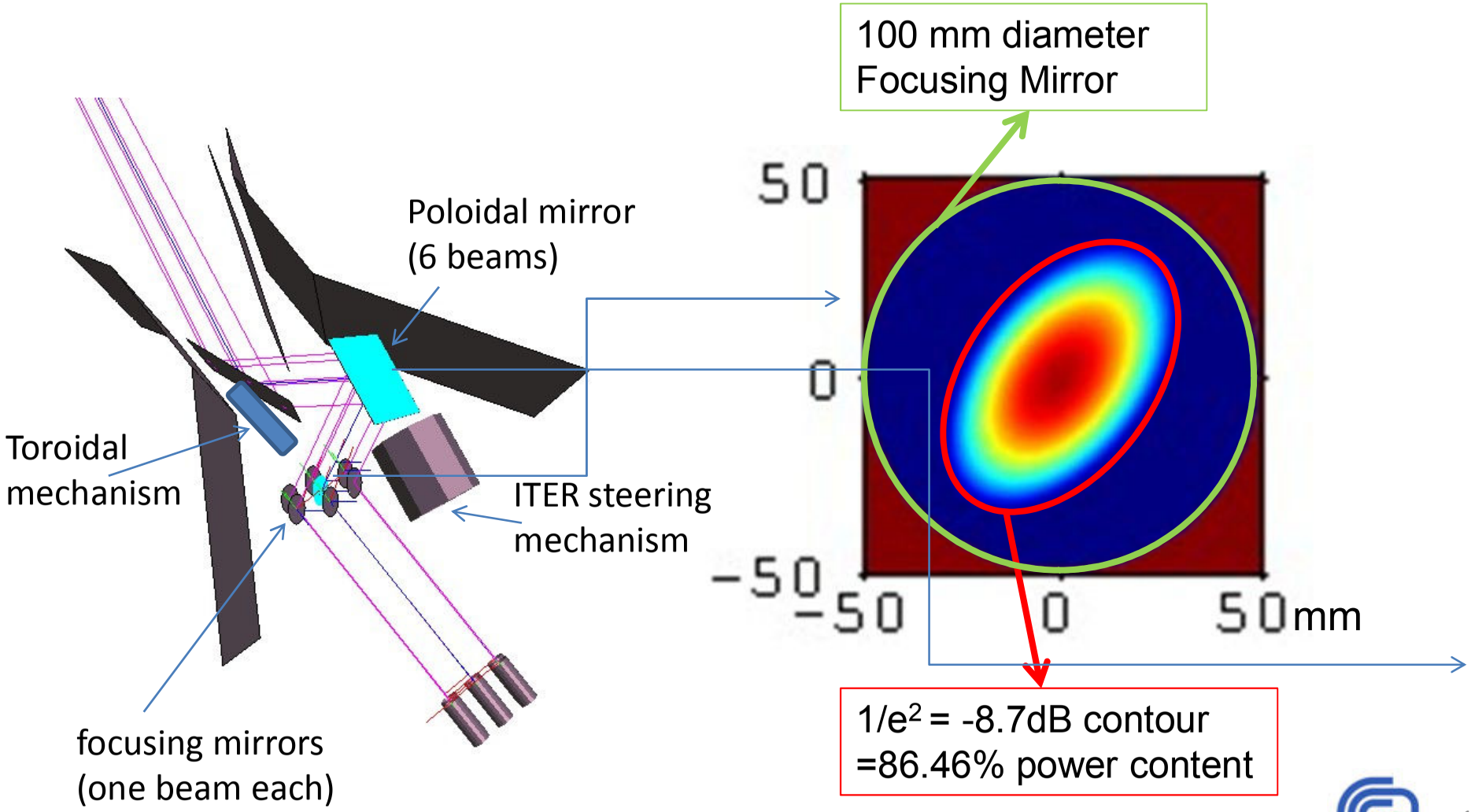


- Approx. comparison of the beam size for the various options (on R scale)
- Dots computed including finite mirror effects
- Layout with steering mirror closer to plasma (L1) has intrinsically a smaller spot size of the single beam in the plasma (~ 40 mm).
- But beams more diverging among themselves

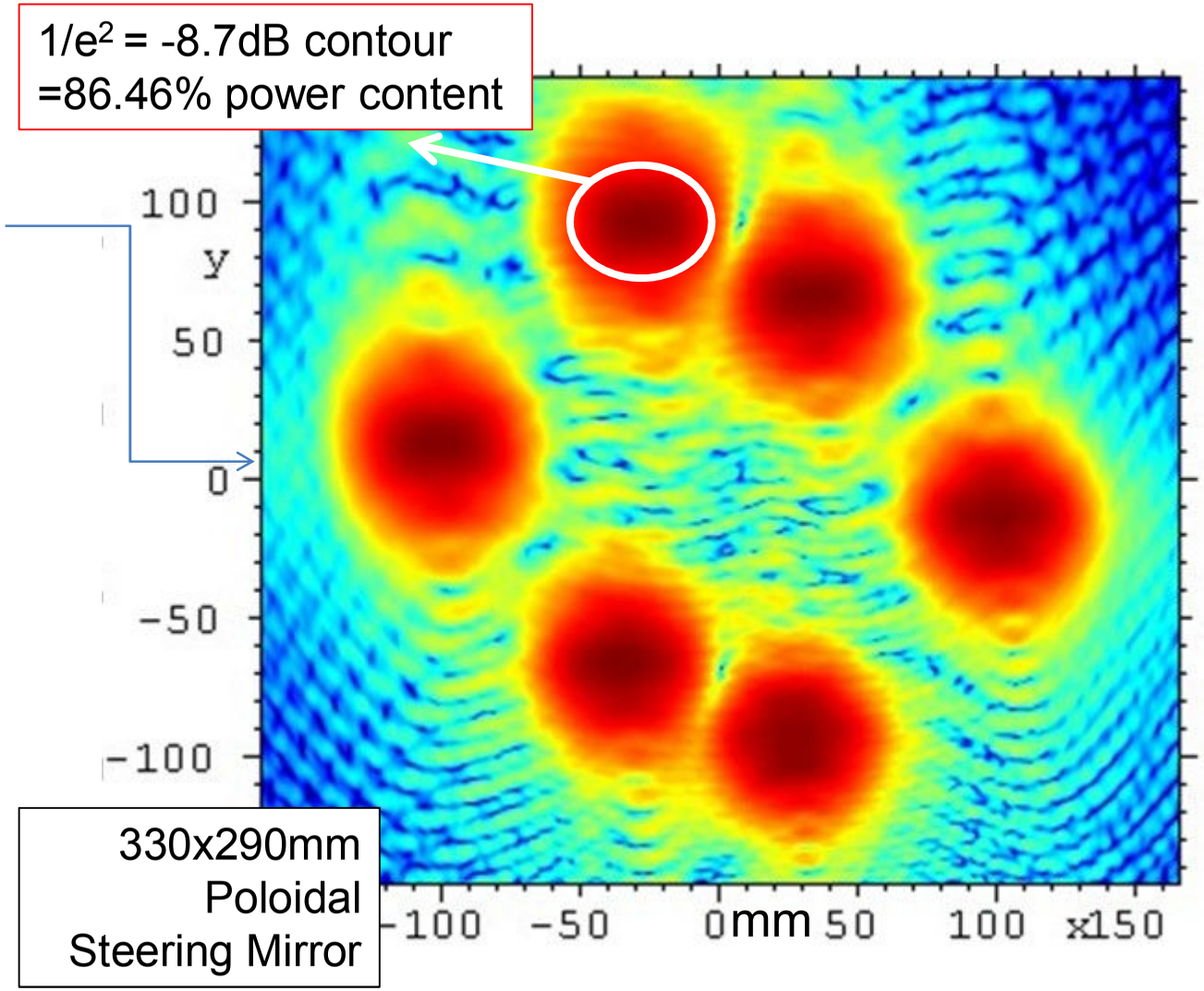
•Solid line: Gaussian beam evolution. Dots: Physics Optics computation

• Room for further optimization of the mirror size (L4)

Beam footprint on the focusing mirror evaluated with Physics Optics computation (L4 option)

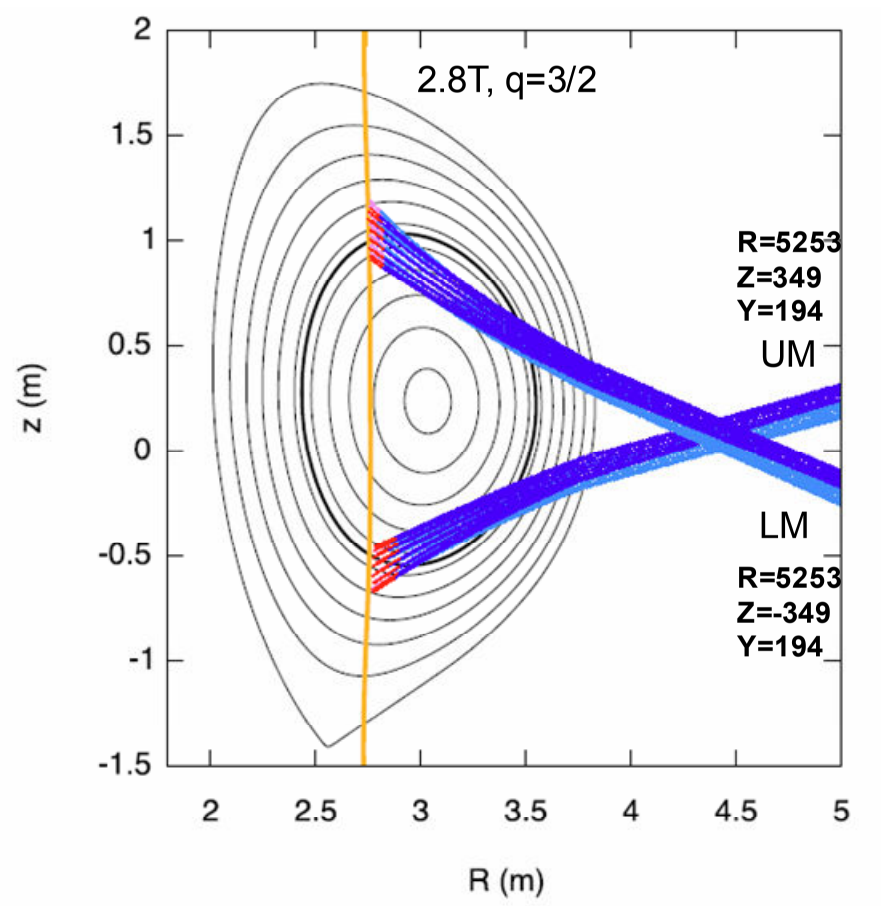


Power density and beams distribution on the poloidal steering mirror evaluated with Physics Optics computation (L4)



- *beam footprints on the poloidal steering mirror (L4 option).*
- *The peak power density is 97 kW/cm² assuming 1MW beam power.*
- *The average power density in the beam radius (white contour) is 55 kW/cm².*

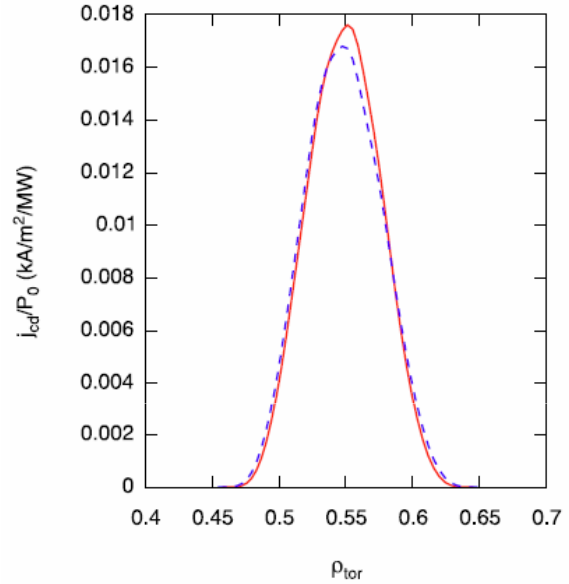
Study of the beam superposition on plasma target

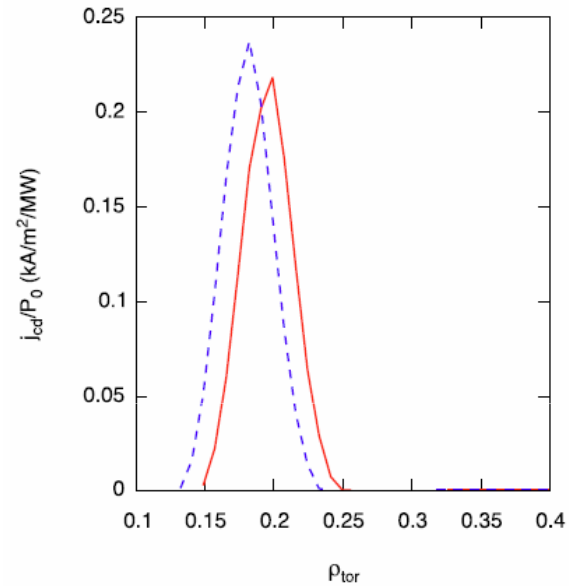


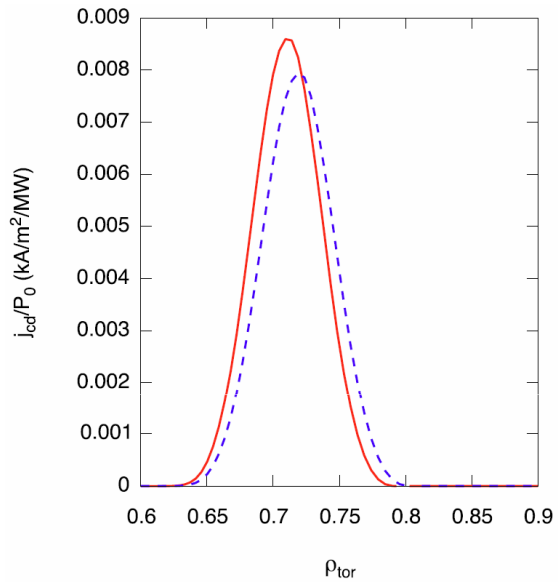
Beam tracing for 2.8T, q=3/2 case

- Optimization criterion: maximum current density achievable for NTM control.
- Convergence computed for q=3/2 surface at B_0=2.8 T
- Current profiles overlap evaluated at B_0=2.6-3.2T
- Convergence of beam launched at different z position of the same module achievable by means of orientation of the focusing mirrors.
- Large distance from focusing mirror to plasma is an advantage for beam convergence

Driven current/power density







Driven current density: *Optimized convergence on target: dα=2° for separation dz=10cm (UM) 2.8T Hmode, q=3/2 (73344);*

Driven current density: *Example of "worst case" (UM) 3.2T AT (77895) q=2*

Driven current density : *(UM) 2.6T Hmode (73344) q=2*

- Estimate of beam superposition shows small (<20%) broadening of total EC driven current profile in the range of B=2.7-3.3 T

Conclusions

- The work done until this point seems to indicate **option L4** as a promising solution. **L2 (L1)** possibly as back-up solution.
- A few points still require attention in this preliminary design phase. Essential issues to be assessed are:
  - Completion of the optical optimization (exploration of the steering range with PO computations)
  - Improving of focusing (smaller beam size) possible using a mode converter. Optimization of the size of the focusing mirrors
  - Analysis of losses (considering options for the materials)
  - Definition of the toroidal steering mechanism
  - Stress analysis, particularly of the side reflectors.
  - Thermal load on the mirrors
  - Design of the mirror cooling circuit

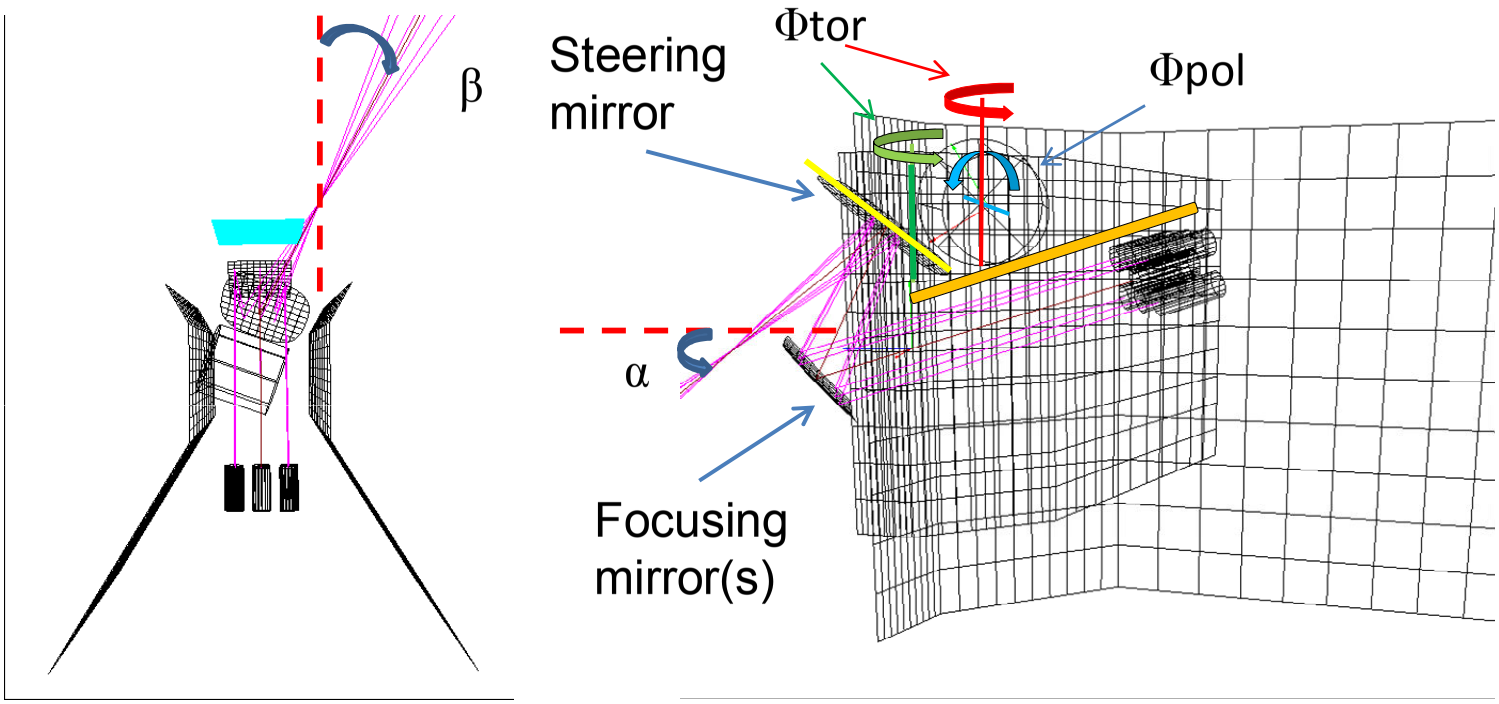
Thank you
for your attention

你好！

(I hope this means “ciao”…)

Backup slides

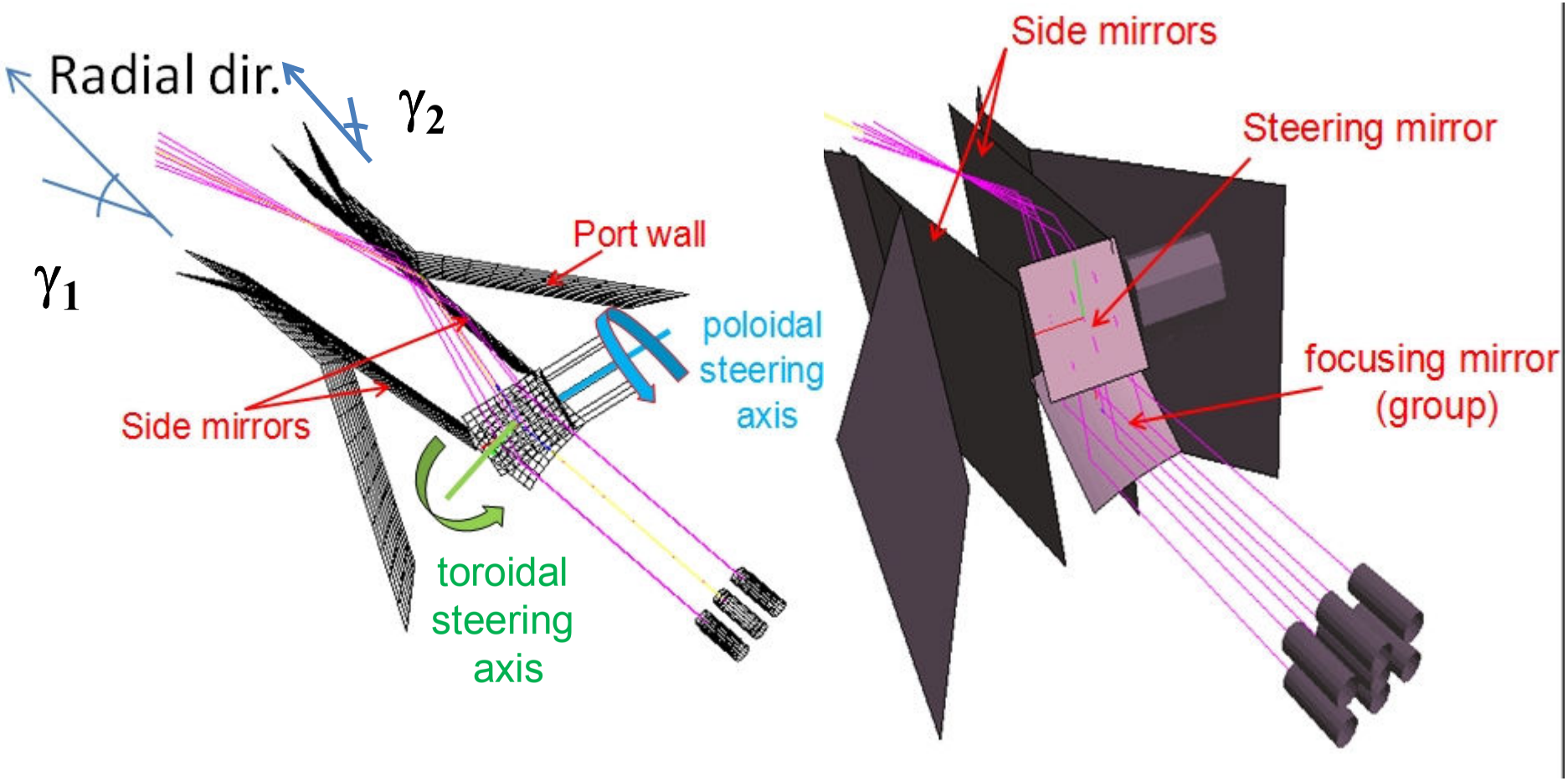
Option(s) L1: steering mirror in narrow part of the JET port, modified ITER-like mechanism for poloidal steering, with different (yet unidentified) possibilities for toroidal steering



Variants for L1

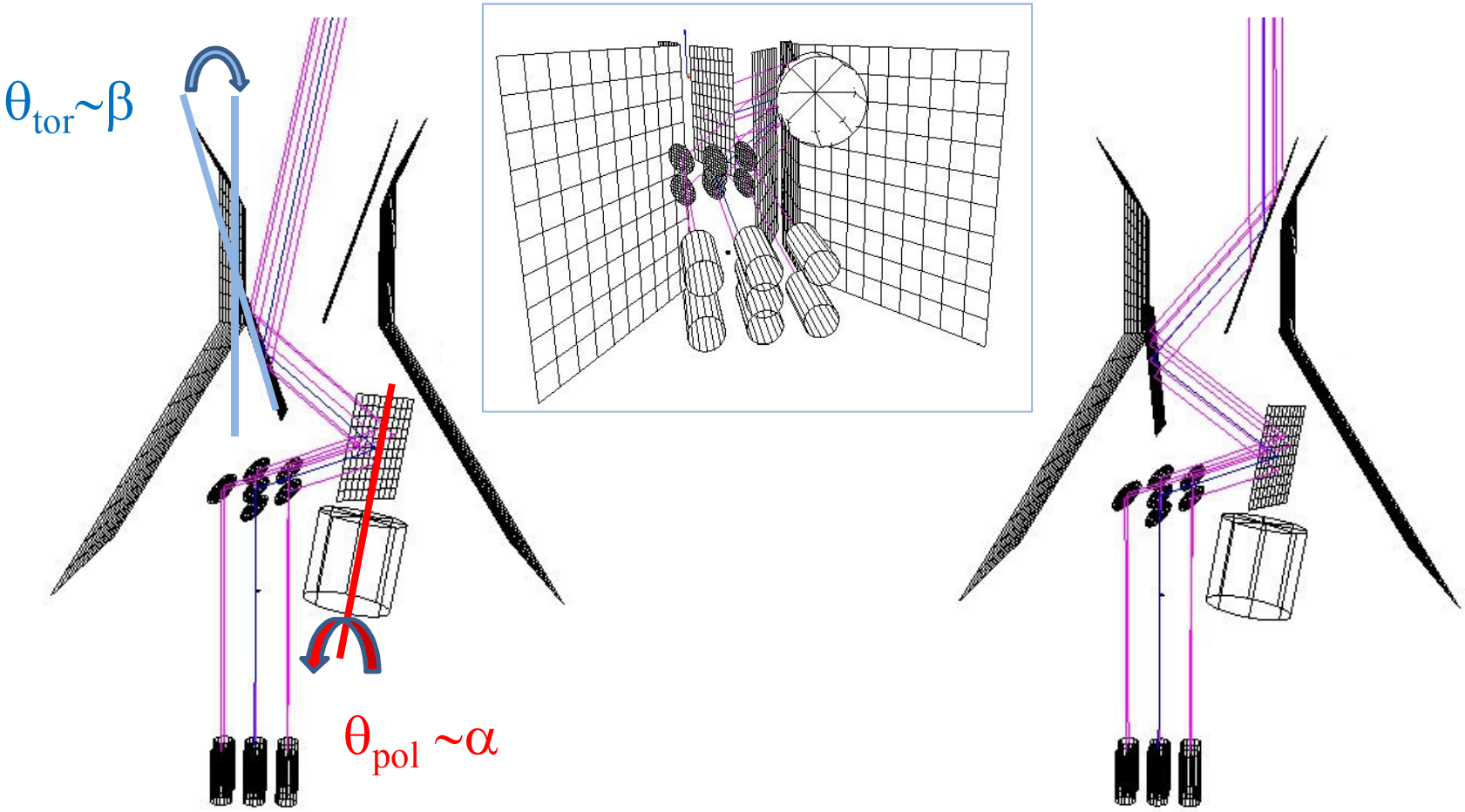
L1-ti	Toroidal movement onto poloidal frame (yellow axis)
L1a1	Poloidal movement onto toroidal frame (red axis)
L1a2	Poloidal movement onto toroidal frame advanced towards plasma (green axis)

Option L2: ITER-like mechanism in the back of the JET port for poloidal steering. Toroidal steering obtained moving the whole mechanism and bouncing technique is used to get a set of discrete toroidal angles



Poloidal movement onto toroidal frame

Option L4: ITER-like mechanism in the back of the JET port for poloidal steering. Toroidal steering obtained moving one of the side mirrors and bouncing technique is used to get continuous range of toroidal angles



1 bounce

2 bounces

L1 steering range

option L1a2	phi_tor°	|Beta°|	phi_pol°	alpha° (>0 downward)	target
UM launch point R=4471, z=309	0.00	0.00	1.20	4.00	z=23mm (plasma centre)
	5.00	7.30	3.00	12.40	z=0 (vessel midplane)
	10.00	15.50	11.50	29.00	z=-54 (q=3/2)
	15.00	21.70	14.00	34.30	z=-80 (q=2)
	20.00	29.50			

L2 steering range (with gaps in toroidal angle)

option L2	phi_tor(°)	beta(°) (co >0)	bounces
UM Poloidal range: -2.7°<alpha<28,4° (0°<phi_pol<15°) Virtual launching point (VLP): R=5600, z=360	-25	-21.6	1
	-20	-17.34	1
	-15	-12.38	1
	10	-8.4	0
	5	-4.1	0
	0	0	0
	-5	4.61	0
	25	9.5	1
	30	14.16	1
	-35	18	2
	-40	23	2
	-45	27.7	2

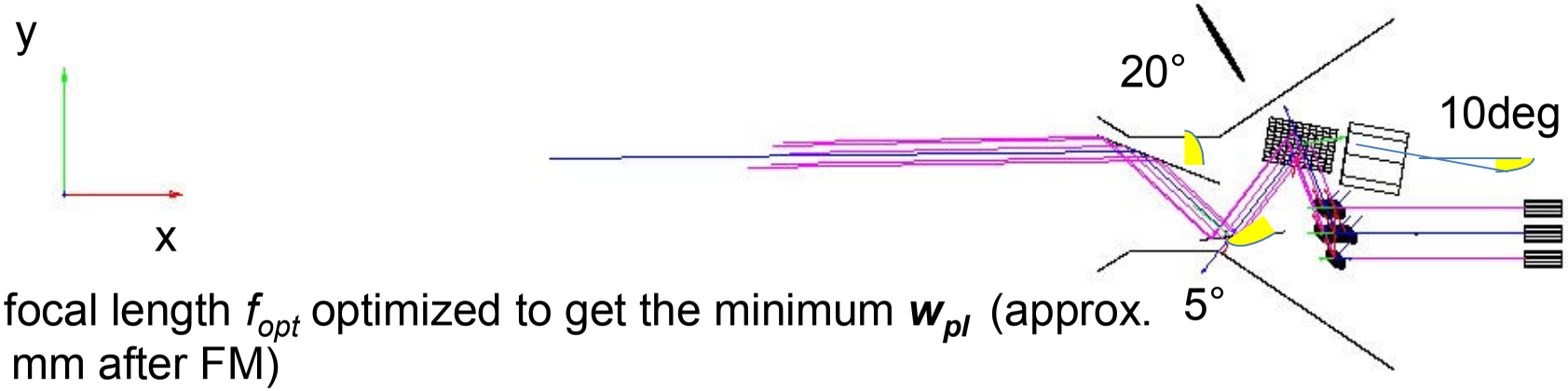
γ_1=6°, γ_2=0°, different choice gives different toroidal range

L4 steering range
(NO gaps in toroidal angle)

Option L4				
theta tor	Beta (alpha=0)	Bounces	theta pol	alpha (Beta=0, theta tor=26.5)
-5	-23	1	18	-1.8
0	-12.8	1	20	1.5
6	-0.5	1	33	24.5
6.5	0	1		
30	-7.5	2		
26.5	0	2		
20	12.5	2		
15	22.8	2		
13	26.8	2		

Focusing optics calculations (L4)

Starting from a preliminary geometric model of the launcher (optical elements positions and orientations) the needed shape of the focusing mirror (**FM**) was determined.

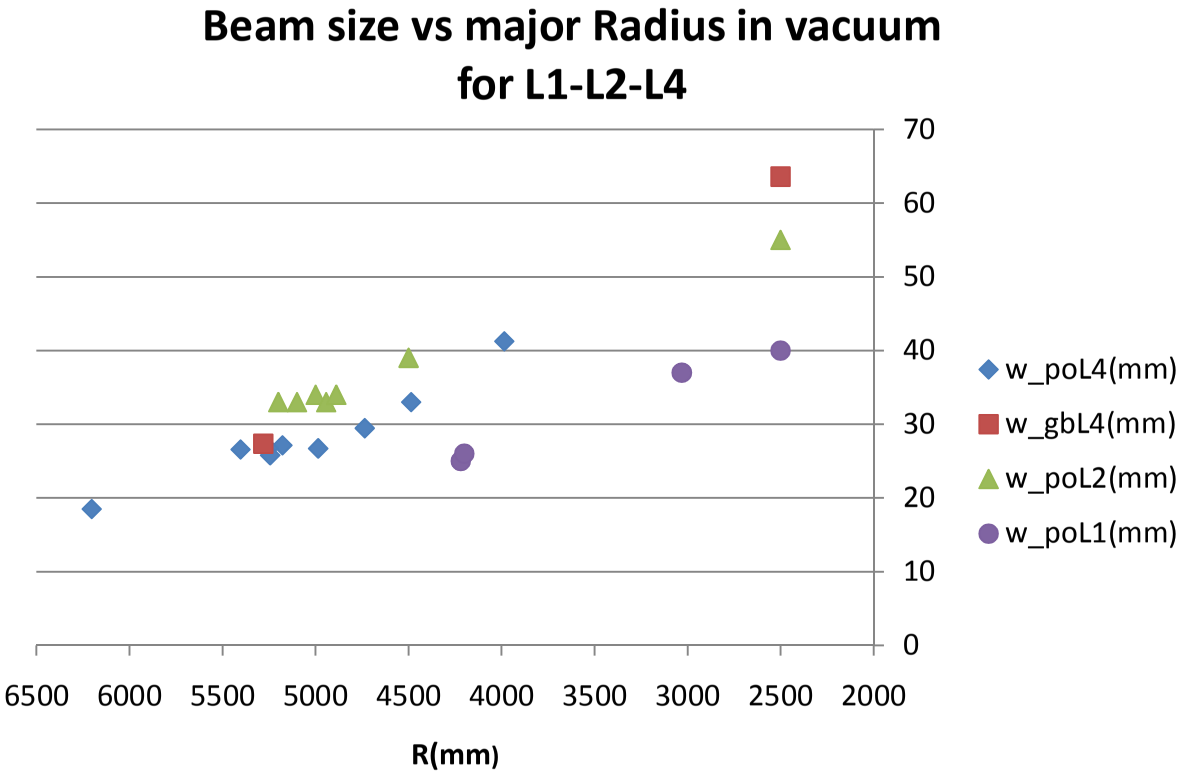


- FM focal length f_{opt} optimized to get the minimum $\boldsymbol{w_{pl}}$ (approx. 3400 mm after FM)
- from the input beam parameters, resulting w_{0out} , d_{0out} are calculated;
- curvature radii of incident and reflected wavefronts can thus be used to determine positions of the foci (F_1, F_2), ellipsoid orientation and parameters (A, B, C) with the aid of the geometric model.

Summary for L4 optics:

Option	w_{0in}	d_{0in}	w_{FM}	f	d_{0out}	w_{0out}	w_{pl}	A	B	C
L4	20.4	800	30.0	1037	619	27.1	63.6	2446	1304	2069

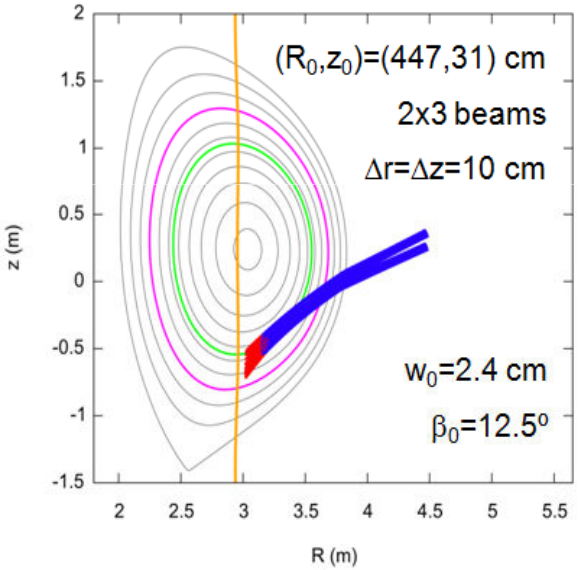
Beam size vs major Radius in vacuum for L1-L2-L4

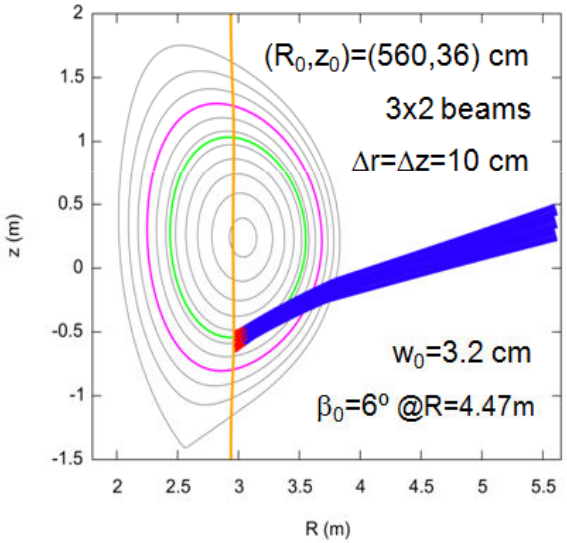


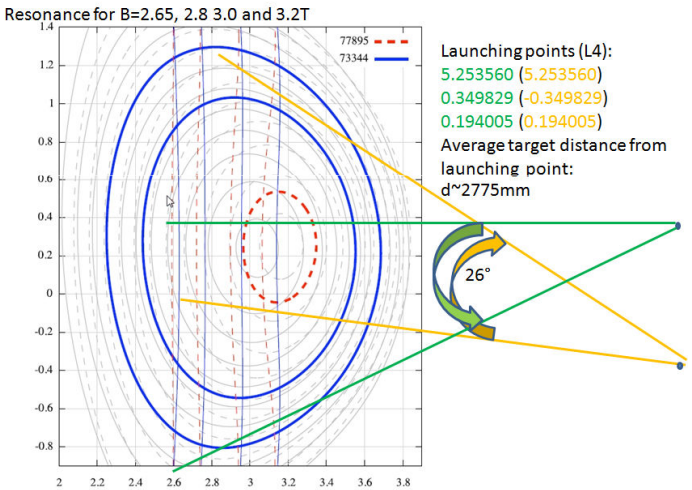
Larger beam size for L2 (L4) is mode than compensate by better beam superposition properties (see later)

Beams superposition study: finding optimal geometric convergence using orientation of individual focusing mirror for max driven curren density

- **L1** Upper Module
- **L2** Upper Module
- **L4 TO BE DONE**







- Convergence computed for q=3/2 surface at B_0=3.0T, shot 73344
- Current profiles overlap evaluated at B_0=2.7, 3.0, 3.3T

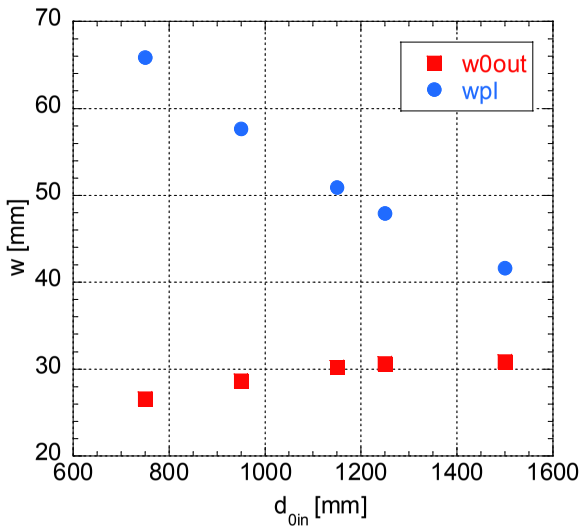
Focusing optics calculations

All launcher options uses one focusing mirror (ellipsoidal surface) along the beam path:

Optimization criterion: ***minimize beam dimension in the plasma.***

Optical parameters:

- w_{0in} : input beam waist (20.4 mm at WG's tip)
- d_{0in} : input distance from waveguide to focusing mirror (***port expansion is required for L2 and L4 options***);
- f : focal length of equivalent thin lens;
- d_{0out}: output beam waist location;
- w_{0out} : output beam waist;
- w_{pl} : beam dimension at absorption location in the plasma (approx. R=2500 mm)



As expected: larger input distance d_{0in} gives better focusing in the plasma w_{pl} , with less appreciable effects on w_{0out}