Numerical and experimental investigations of a microwave interferometer for the negative ion source SPIDER

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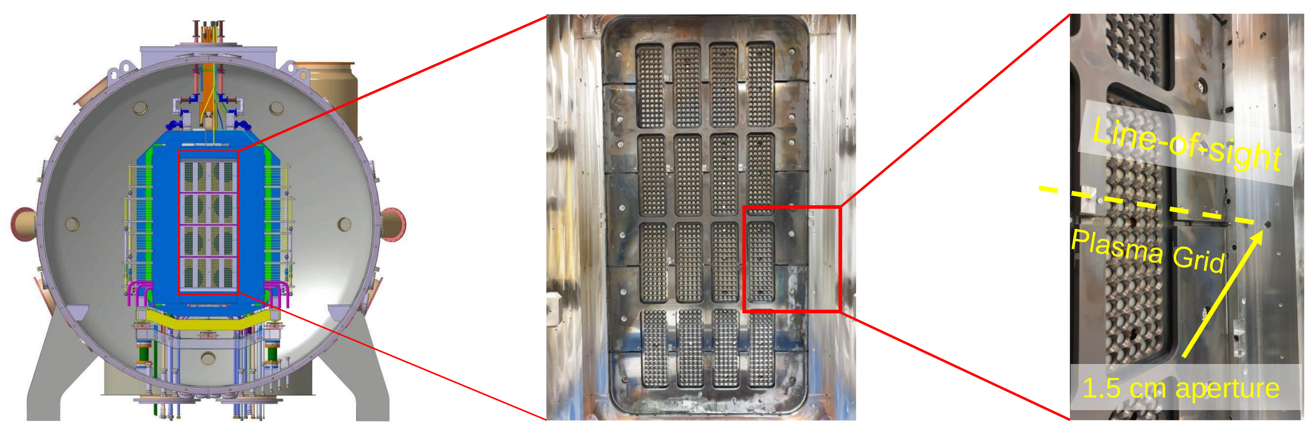
INTRODUCTION

- The problem of the excessive amount of co-extracted electrons is crucial in the operation of negative ion sources for Heating Neutral Beam injectors [1, 2].
- It would be very helpful to rely on a direct and non-invasive measurement of **plasma electron density** in front of the Plasma Grid (PG) where negative ion survival depends on the electron density and temperature.
- The negative ion source SPIDER (Consorzio RFX, Italy) is investigating the physics of large negative ion sources in hydrogen and deuterium with particles accelerated up to 100 keV. [3]
- Mm-wave interferometry has already been successfully tested on a negative ion source for fusion [4, 5]. For SPIDER, the mechanical and electrical constraints make the use of such a system quite challenging.
- During 2020, exploratory studies began and it was agreed that a ≈**100 GHz** microwave (mw) **system** was reasonable choice considering the SPIDER typical plasma density in the plasma expansion region and the availability of an almost plug-and-play 100 GHz interferometric setup. During 2021, 2D numerical simulations of microwave propagation through SPIDER accelerator were finalized. In 2022, preliminary experiments on a test bench mimicking SPIDER geometry have been carried out.

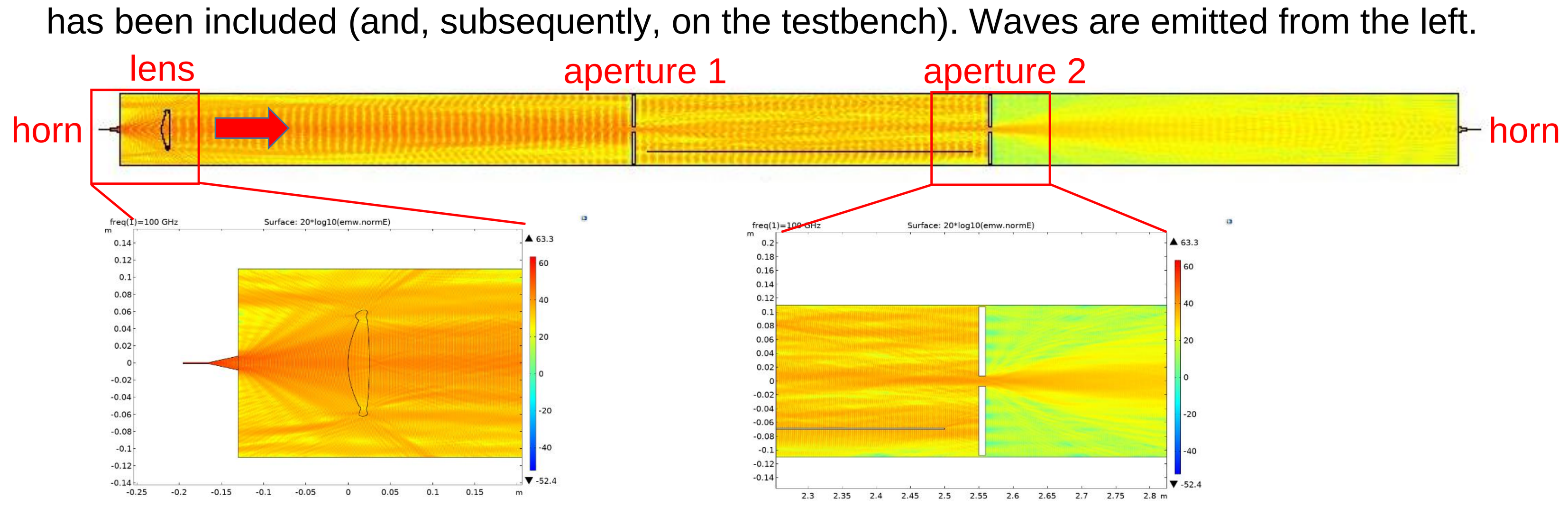
NUMERICAL SIMULATIONS

- The main issue is that access to the plasma in the expansion region is strongly limited by the small size of apertures on the metal case surrounding the acceleration grids. The only access to the plasma that might be available has 1.5 cm diameter and corresponds to a line of sight located at about the middle of the third segment and displaced by 7 cm from the PG surface.



Left: cross section of SPIDER. *Center*: Photo of the grids facing the plasma. *Right*: Photo from the interior of the plasma source marking the position of a 1.5 cm aperture at 7 cm from the PG

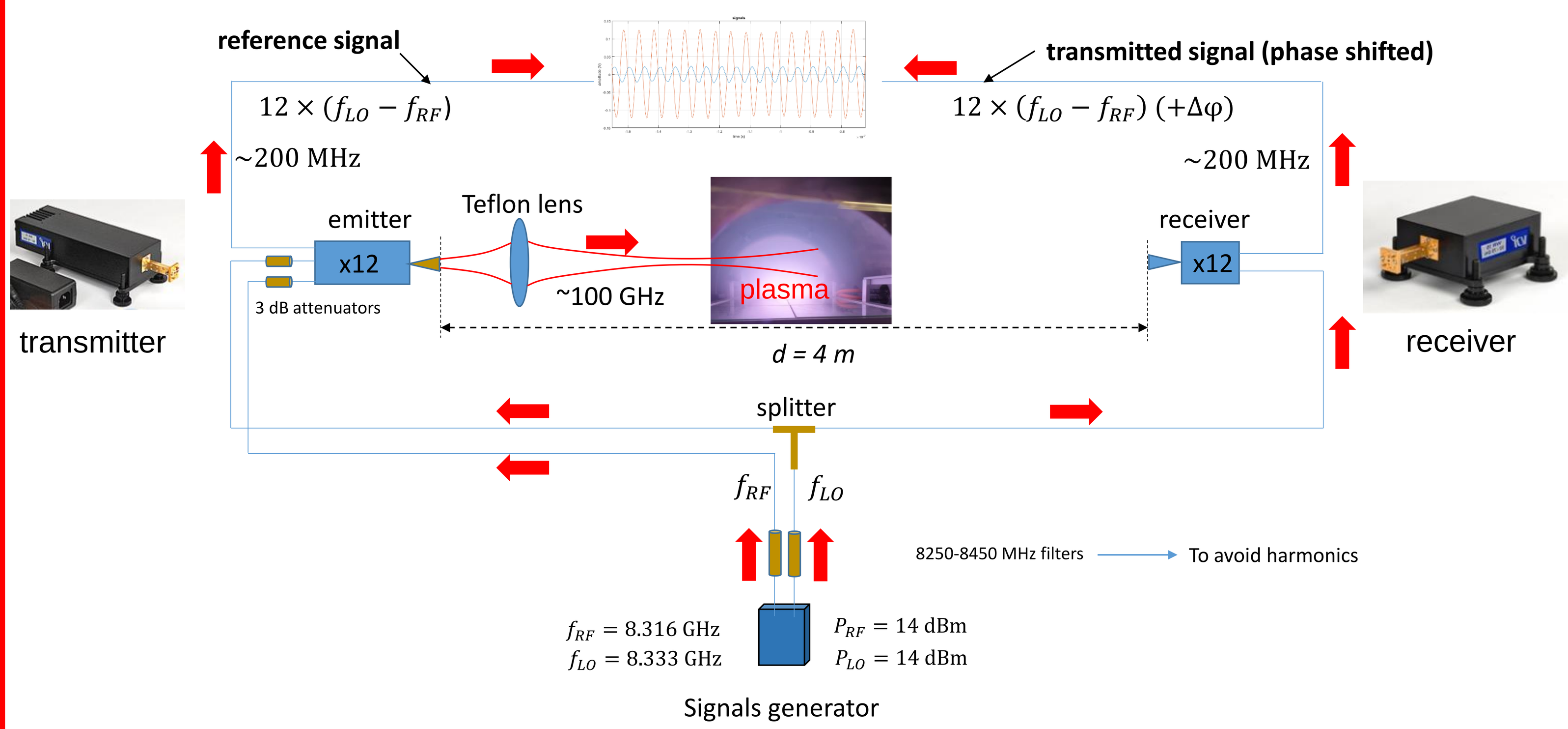
- Full wave 2D simulations: Custom WR-10 horns, simply two accesses simulating the available apertures (1.5 cm wide), the reflecting grid, a focusing Teflon lens in front of the emitting horn has been included (and, subsequently, on the testbench). Waves are emitted from the left.



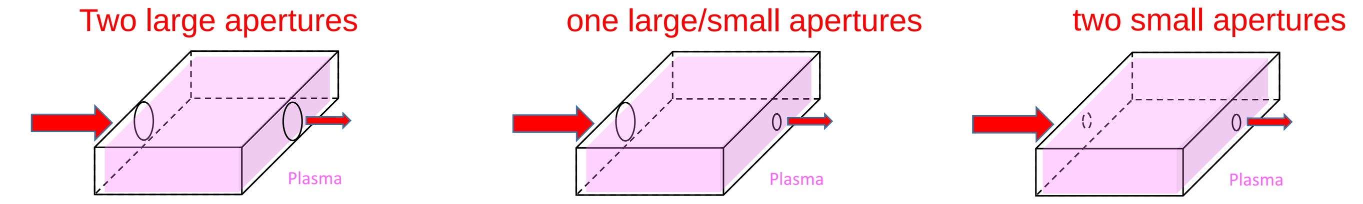
- A focusing lens in front of the emitting horn provides a considerable help for beam transmission along the entire path.
- Multipaths are generated in between the two apertures and by reflections on the PG but a non negligible amount of the signal is anyway transmitted downstream to the receiver.
- The intensity reduction of the signal after propagation through the entire vessel is expected to be about 4 orders of magnitude.

EXPERIMENTS ON A TESTBENCH

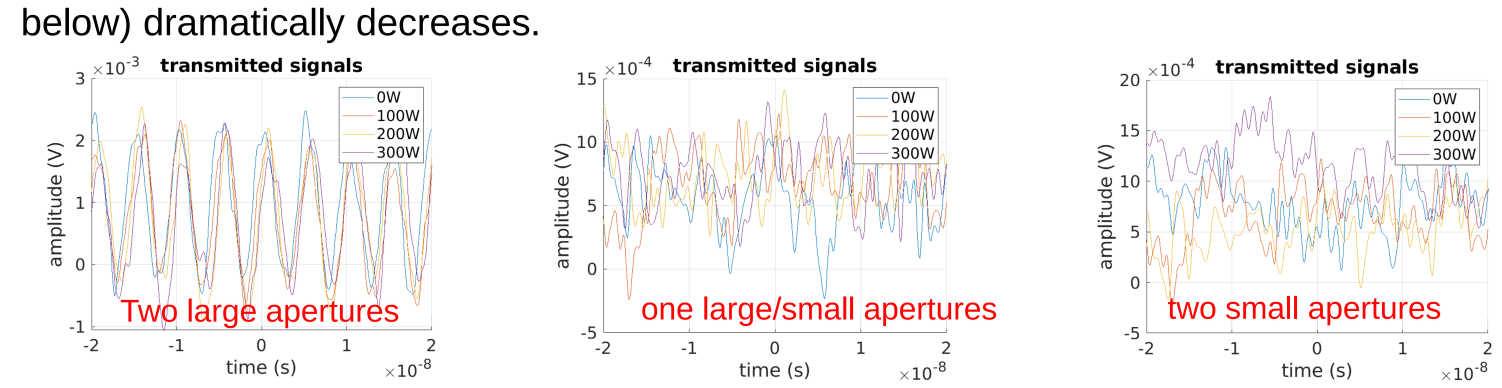
- A setup mimicking SPIDER dimensions including access constraints and the possibility to produce a plasma of density similar to that of the expansion region has been set up and tested at the SPC industrial plasmas laboratory.
- The system is an heterodyne interferometer with a reference local oscillator frequency (LO) and a probing frequency (RF) [see the scheme below for further details].



- The SPIDER testbench consists of a vacuum vessel in which a uniform plasma layer can be produced by a resonant RF antenna in a planar geometry [6], attaining a density of 10^{17} m^{-3}, similar to SPIDER plasma density in the expansion region.

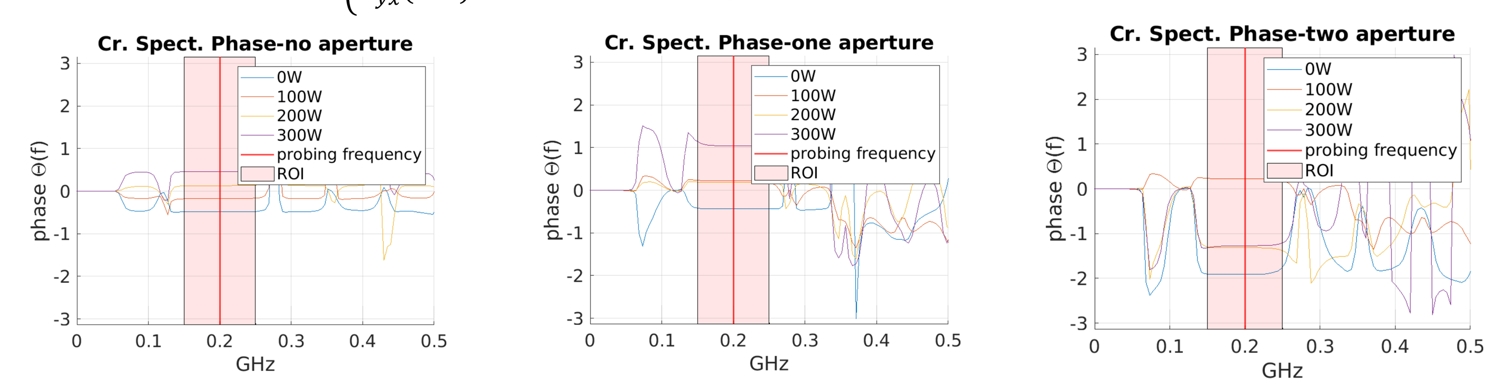


- The microwave transmission is tested through 8 cm diameter window and also through 1.5 cm diameter apertures, including the presence of plasma at different densities. When the mw beam is limited by the 1.5 cm apertures, the S/N ratio of the transmitted signal (shown below) dramatically decreases.



- Due to the large S/N ratio on the transmitted signal, **cross correlation analysis** is required. The cross correlation $\hat{R}_{xy}$ measures the degree of correlation between two time series x_n and y_n. From $\hat{R}_{xy}$, the cross power spectral density $P_{xy}(\omega)$ and, then, the **cross spectrum phase** the can be estimated.

$$\hat{R}_{xy}(m) = \begin{cases} \sum_{n=0}^{N-m-1} x_{n+m} y_n^* & m \geq 0 \\ \hat{R}_{yx}^*(-m) & m < 0 \end{cases} \qquad P_{xy}(\omega) = \sum_{m=-\infty}^{\infty} R_{xy}(\omega)\, e^{-j\omega m}$$

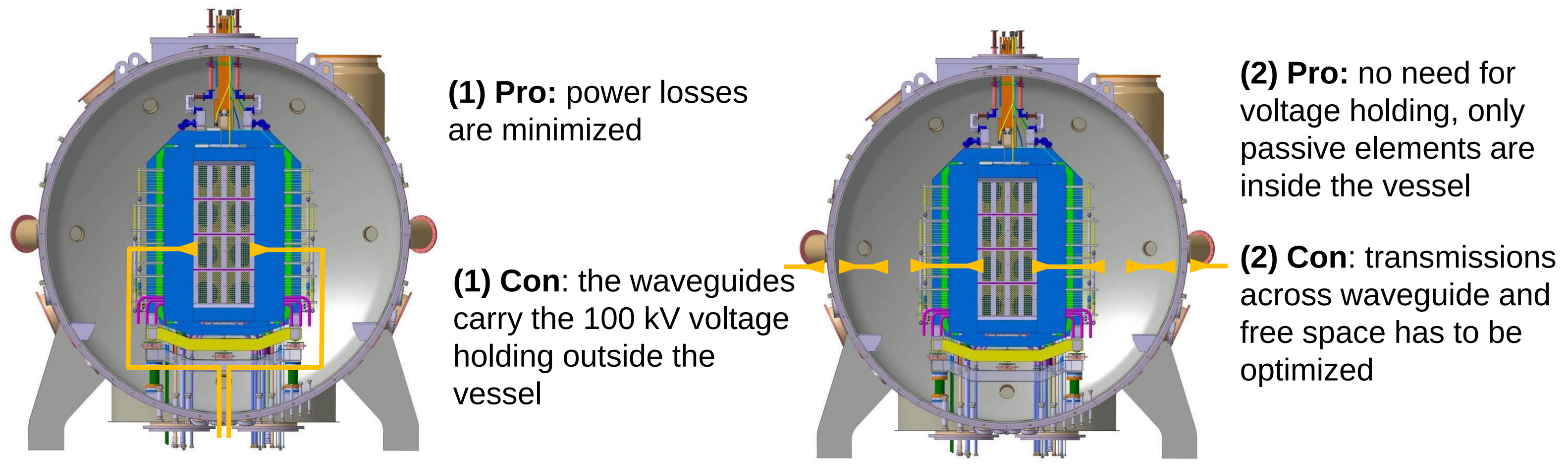


Cross spectrum phase between the transmitted and the reference (LO) signal at different plasma densities with different apertures.

- Although the 4 m distance and the presence of the grid, the system is capable of measuring a phase shift compatible with the variation of plasma density.
- Once only the small aperture is available, the order of the phase shifts is lost.

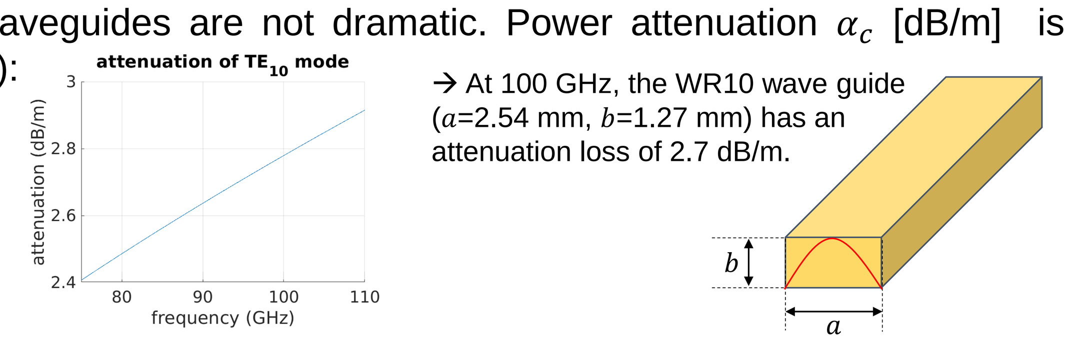
PROPOSALS FOR SYSTEM IMPROVEMENT

- **Two proposals to improve signal transport up to the plasma: (1)** Channeling of the mw signal by waveguides from the bottom bushing; **(2)** Transport through multiple straight waveguides and free space propagation.

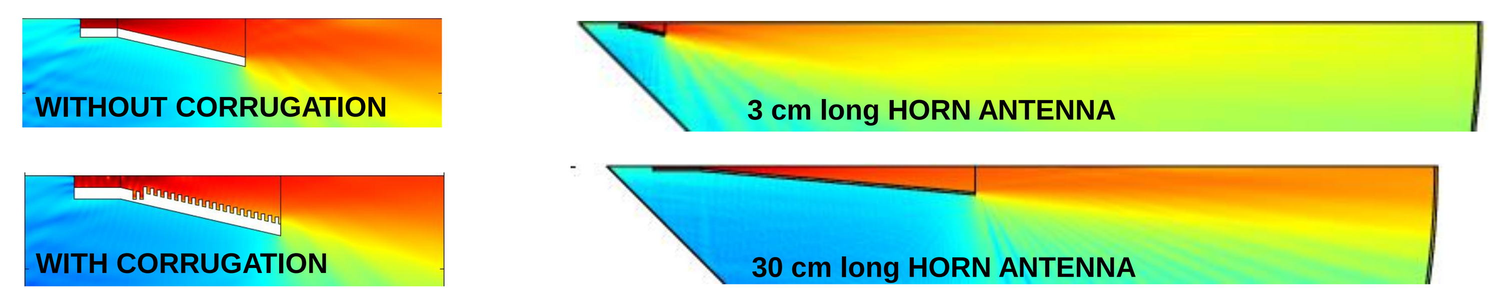


- Power losses over long waveguides are not dramatic. Power attenuation α_c [dB/m] is given by (single TE_{10} mode):

$$\alpha_c = 8.686 * \frac{R_s}{\eta b} \frac{1 + \frac{2b}{a}\frac{\omega_c^2}{\omega^2}}{\sqrt{1 - \frac{\omega_c^2}{\omega^2}}}$$



- **Improve antenna directivity**: internal corrugation and horn dimensions



- The presence of the internal corrugation reduces the intensity of the sidelobes, while by increasing the antenna length, the beam directivity is improved.

CONCLUSIONS

- An exploratory study of a microwave interferometer for a full-size negative ion source is being carried on.
- The current setup of SPIDER is challenging for interferometric measurements based on mm-waves, given the access contraints.
- Preliminary studies on an experimental testbench show that the current interferometric system is able to perform plasma density measurements despite the transmitter and the receiver located 4 m apart and the presence of a metal grid close to the axis of the probing mw beam.
- The experiments on the mockup revealed that, for the moment, it is not possible to perform plasma density measurements by shining a mw beam from outside the vessel in SPIDER.
- Improvement of mw beam propagation to the plasma by multiple segments of waveguide is envisaged.

REFERENCES

[1] R. S. Hemsworth et al., "Overview of the design of the ITER heating neutral beam injectors", New J. Phys. **19** (2017) 025005.

[2] P. Agostinetti et al., "Detailed design optimization of the MITICA negative ion accelerator in view of the ITER NBI" 2016 Nucl. Fusion **56** 016015.

[3] V. Toigo et al., "On the road to ITER NBIs: SPIDER improvement after first operation and MITICA construction progress", Fusion Engineering and Design **168** (2021) 112622.

[4] K. Nagaoka et al.,"Measurement of Electron Density near Plasma Grid of Large-scaled Negative Ion Source by Means of Millimeter-Wave Interferometer", AIP Conference Proceedings **1390**, 374 (2011).

[5] T. Tokuzawa et al., "Upgraded millimeter-wave interferometer for measuring the electron density during the beam extraction in the negative ion Source", Rev. Sci. Instrum. **87**, 11E105 (2016).

[6] Ph. Guittienne et al., "Resonant planar antenna as an inductive plasma source" J. Appl. Phys. **111**, 083305 (2012).

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