TURBULENT BOUNDARY LAYER CONTROL BY FRACTAL SURFACE

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Katsushika Hokusai

The Great Wave off Kanagawa

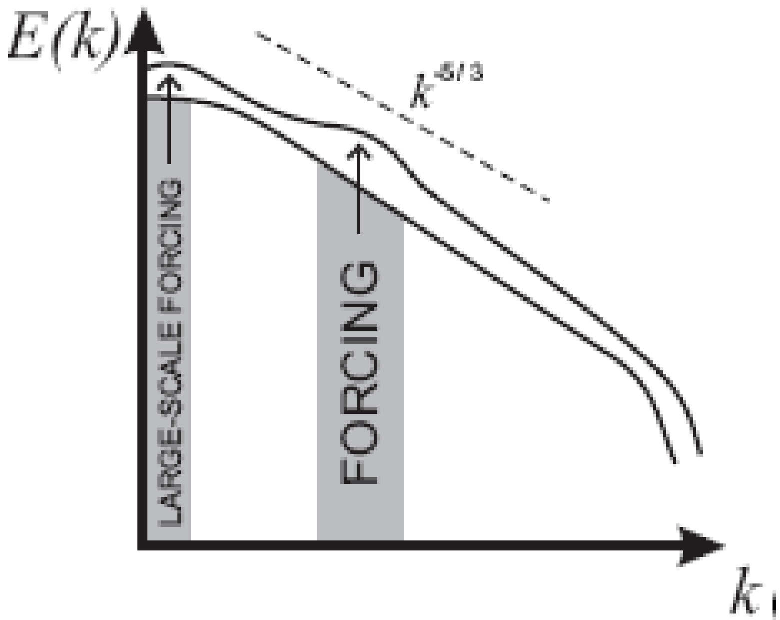
(神奈川沖浪裏 *Kanagawa-Oki Nami-Ura*)

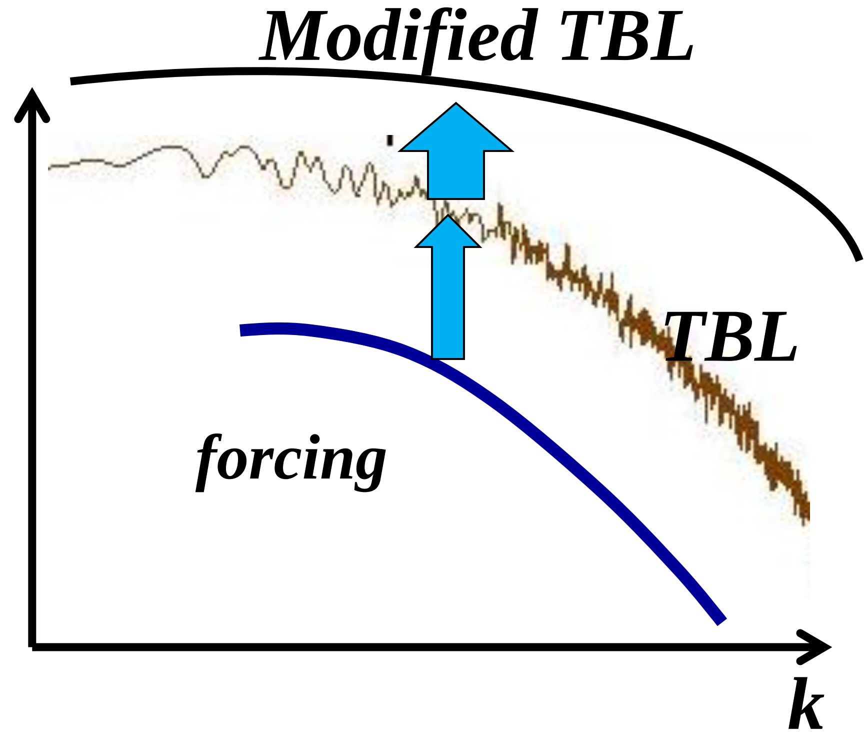
Ivan Aivazovsky

“Chaos. Creation of the World”

1841

Turbulence control
Cascade forcing: approaches





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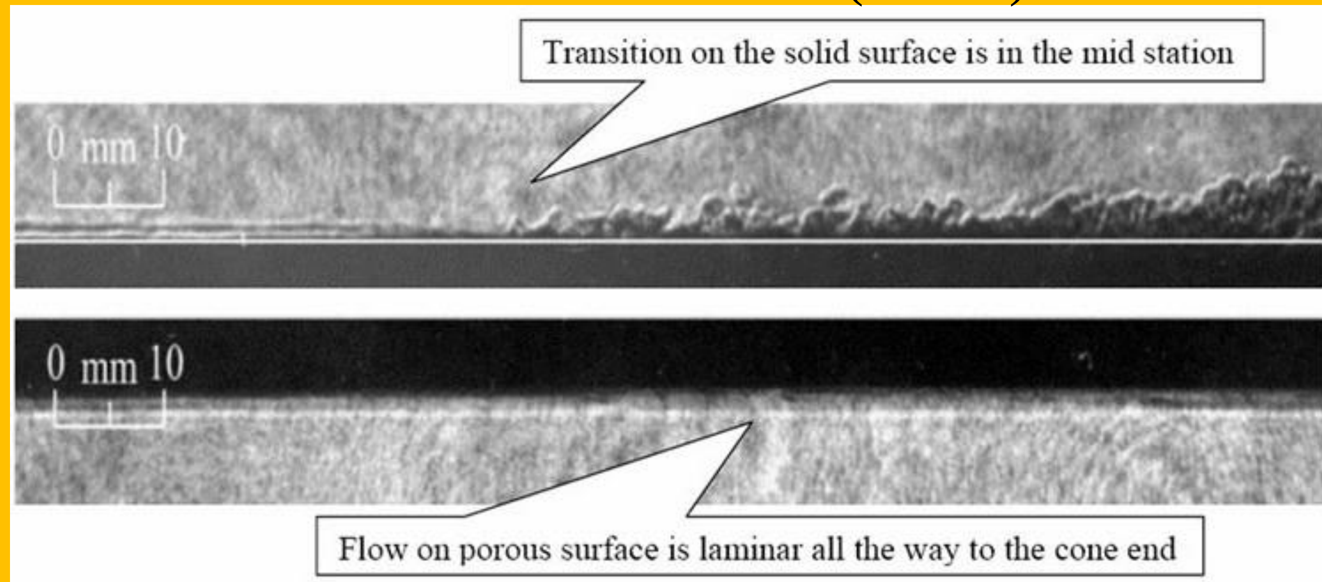
(1) Forcing on large-scale eddies or narrow range – riblets experiments: local modification of cascade

(2) **New approach: forcing in broad range – multiscale forcing on the whole cascade range .**

ULTRASONICALLY ABSORPTIVE COATING (UAC) FOR HYPERSONIC LAMINAR FLOW CONTROL (NASA)



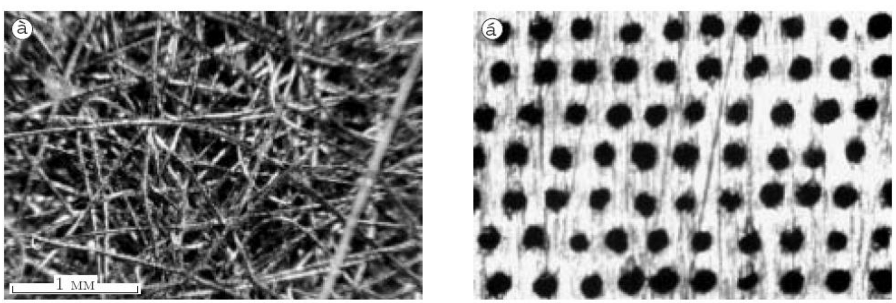


Рис. 1. Пористые покрытия:
а — металлический фетр; *б* — перфорированный лист

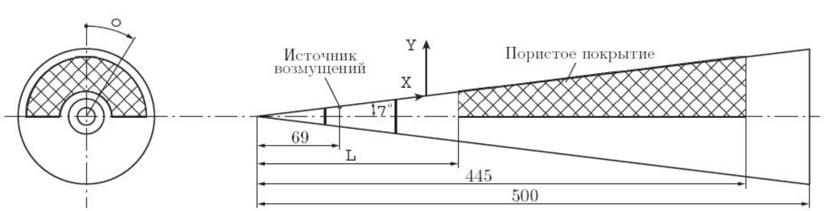
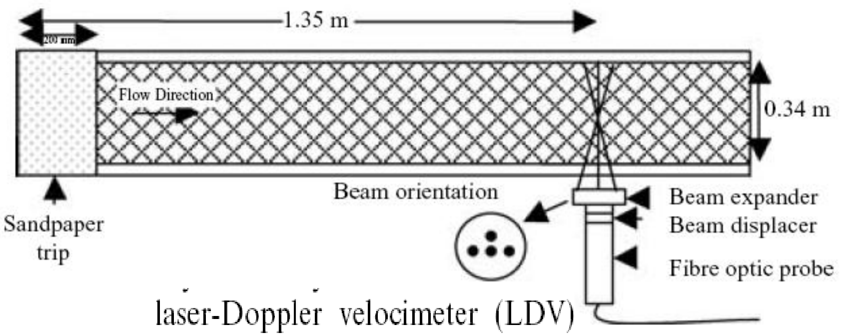


Рис. 2. Схема модели

Hypersonic experiments : roughening of surface , wind tunnel T 326 (ITAM RAS, Novosibirsk) M=5,95 Damping of 500 kHz mode

Previous experiments in the world: rough coatings are helpful for the flow control

M. P. Schultz and K. A. Flack



Experiments with abrasive surface : effect on TBL

Previous experiments: rough abrasive surface forces changing of the TBL

Rough-wall turbulent boundary layer

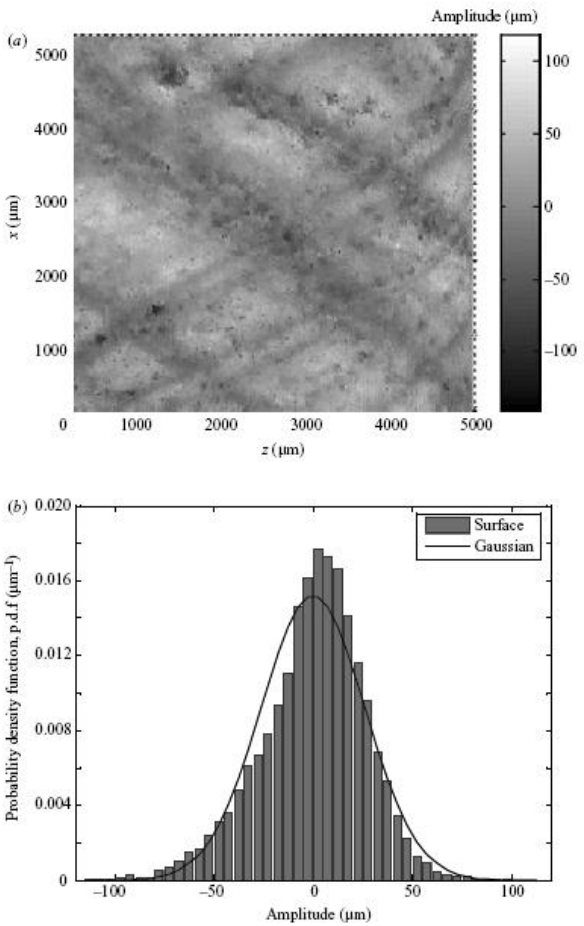
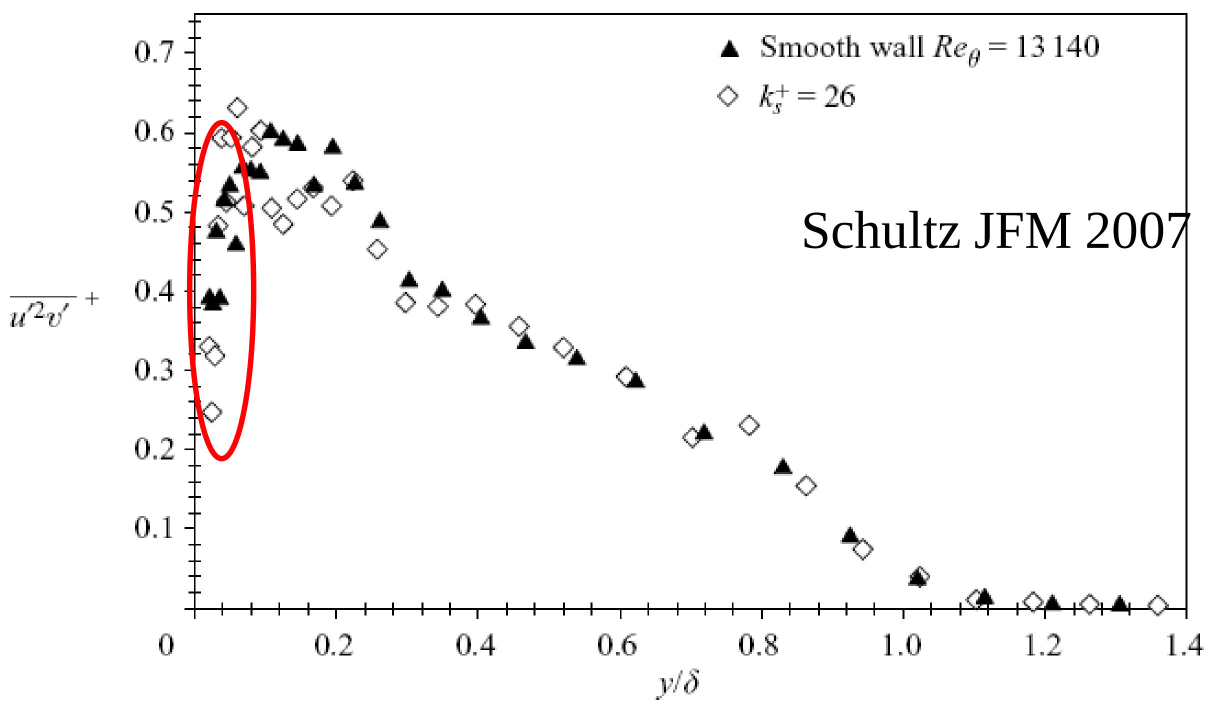


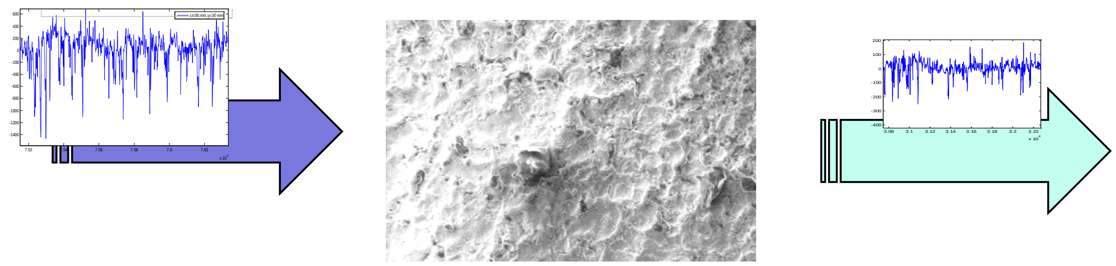
FIGURE 2. Test roughness: (*a*) surface elevation of roughness; (*b*) probabili density function of roughness surface elevations.

Rough-wall turbulent boundary layer



Our new approach to the turbulent flow control

- To use in TBL the **fractal surface of the specific granularity**.



- The **fractal surfaces of roughness** from ~0.5 to ~200 micrometers is formed by the plasma-surface interaction in fusion device QSPA-T.

Budaev, Physica A 382 (2007) 359

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M. Brutyan, V. Budaev, I. Menshov , A.Volkov e a., TsAGI Science Journal, 2013, 4 , 16.

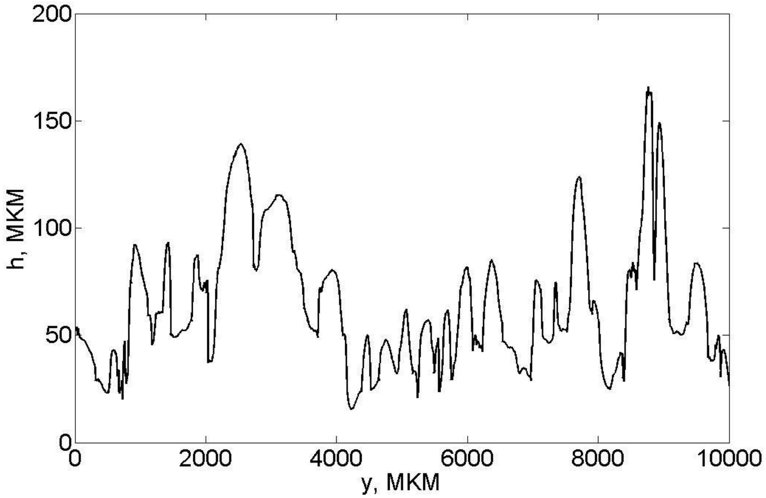
Quasistationary plasma accelerator – QSPA, TRINITI

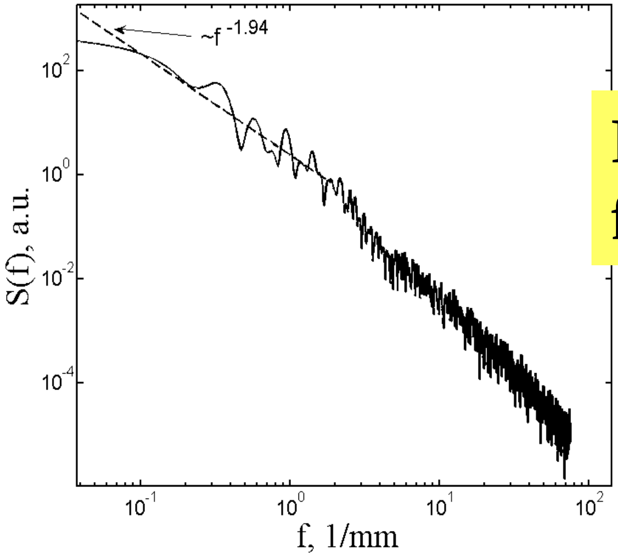
Fractal surface manufacturing by high temperature plasma treatment of material

QSPA plasma parameters:

- Heat load 0.5 ÷ 5 MJ/m^2
- Pulse duration 0.6 ms
- Plasma jet diameter 6 cm
- Ion impact energy 0.1 ÷ 1.0 keV
- Electron temperature < 10 eV
- Plasma density $10^{22} \div 10^{23}\ m^{-3}$

Stainless steel after treatment by high temperature plasma
Specific statistics of rough relief- bursty height's

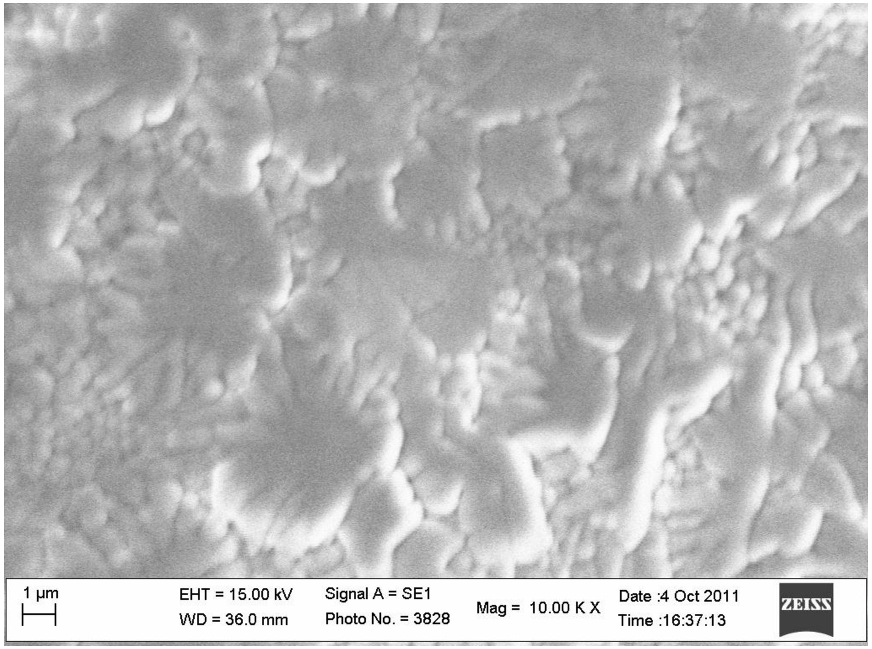


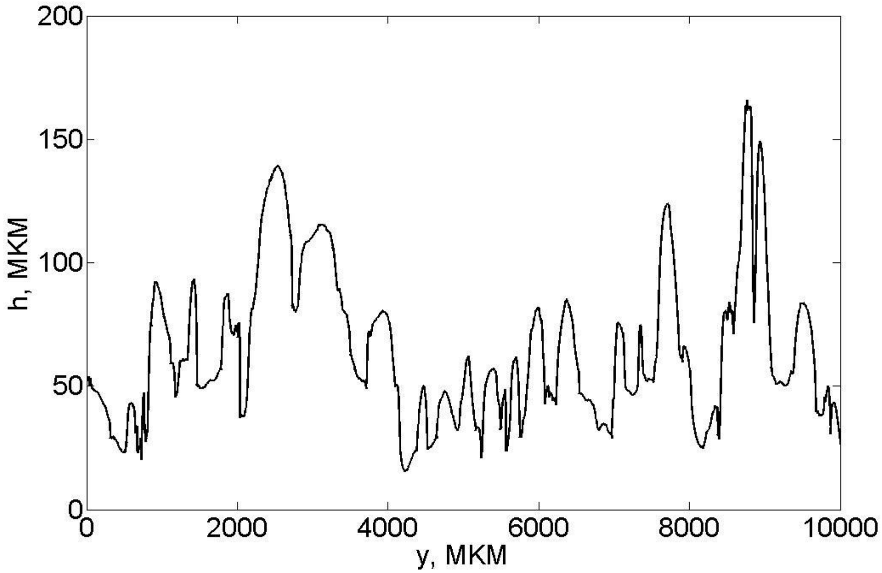


Fractal surface –
fower spectrum rather not flat one

Surface roughness from ~500 nanometers up to ~0,2 mm

after treatment by plasma





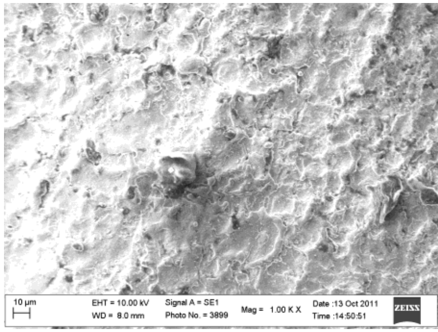
Roughness level is appropriative for the flow control and vortices damping

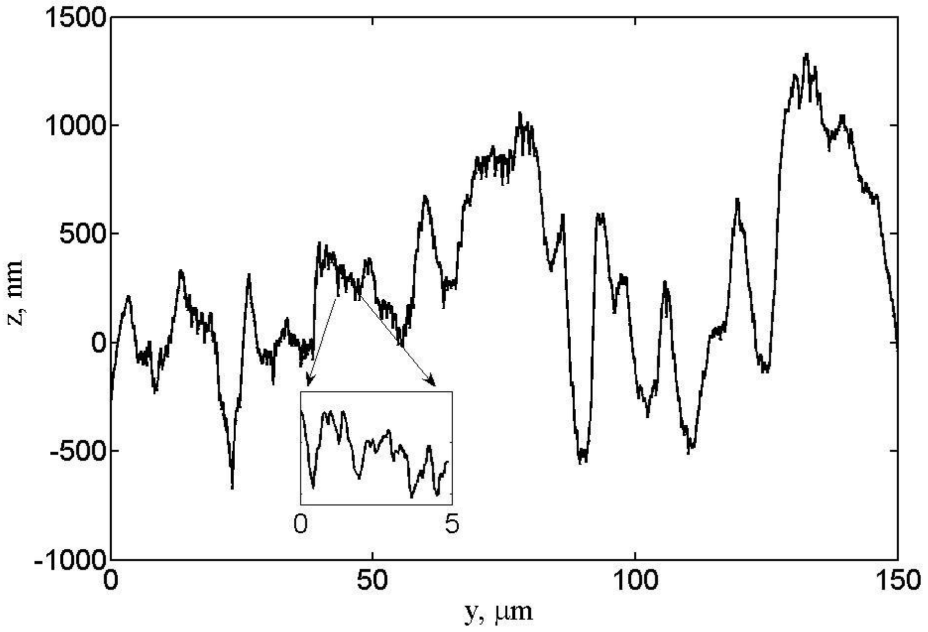
Statistical self-similarity: fractal surface after plasma treatment

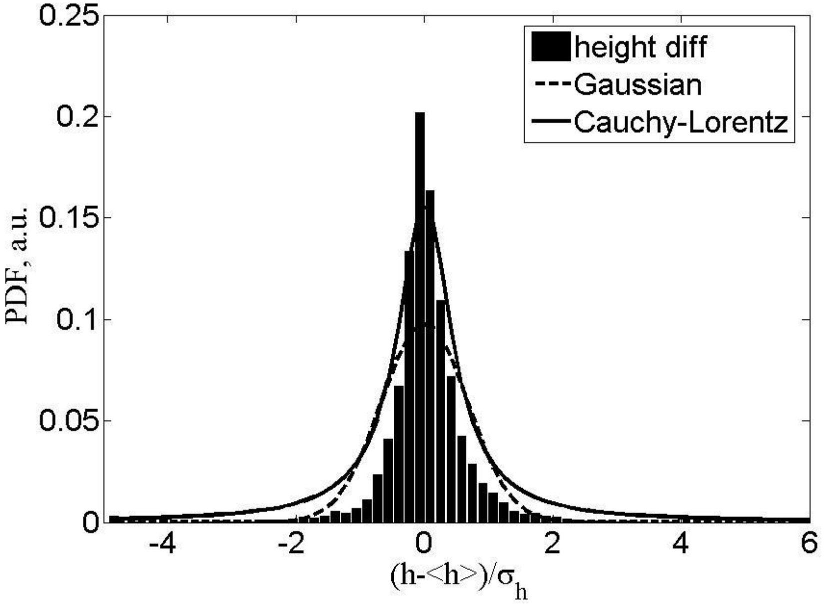
Dilatational symmetry (self-similarity across scales)

probability function (PDF) of profile hights:

$$x \to ax : \; P(x) = a^{-H} P(ax), \; a > 0$$



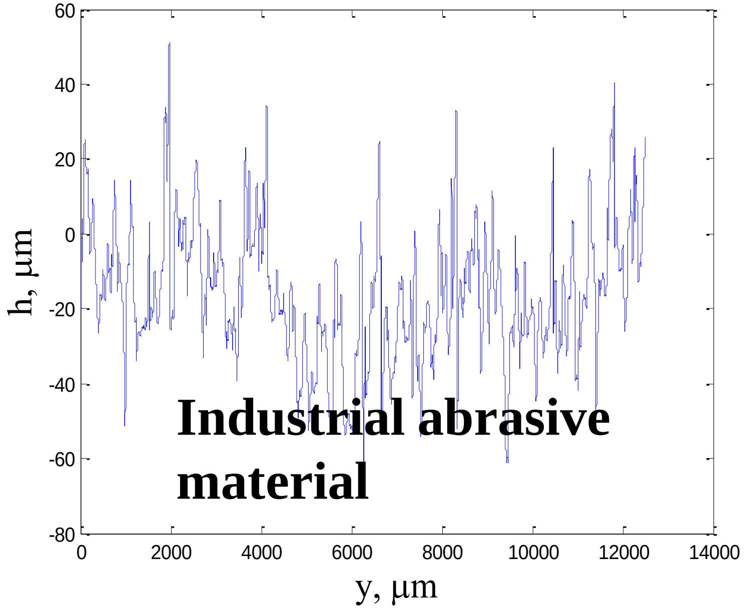


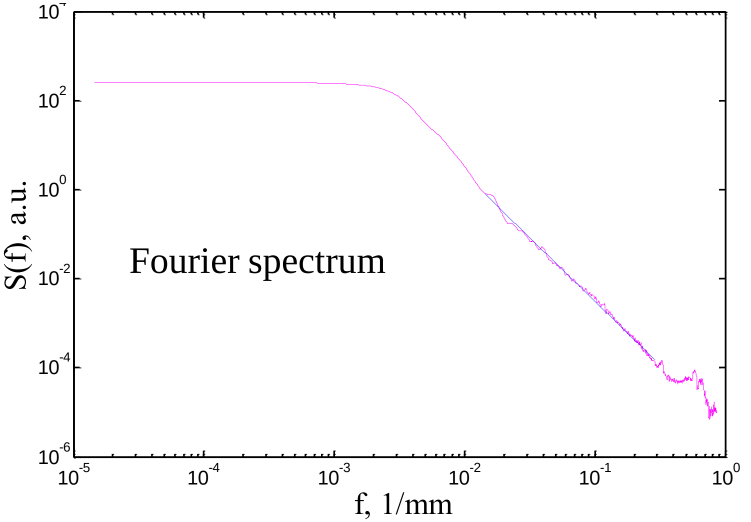


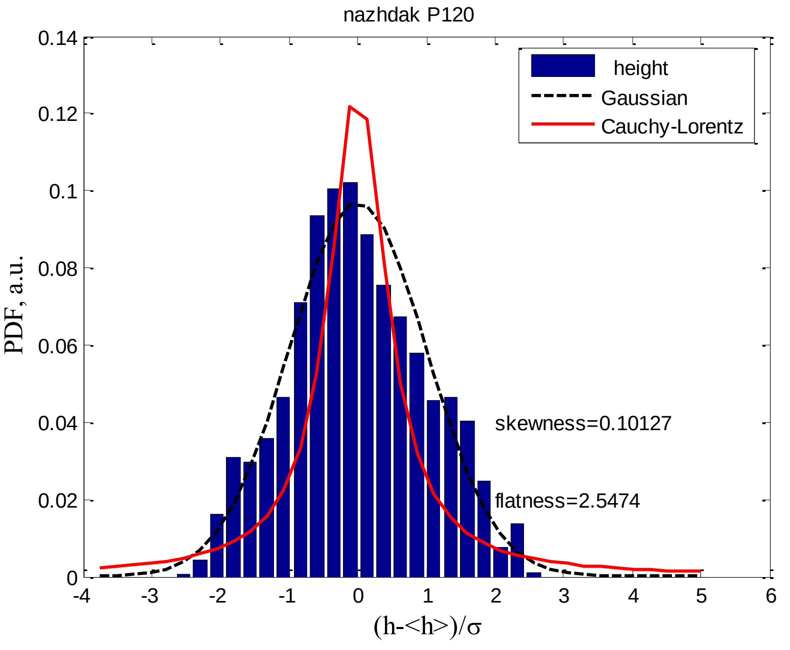
Surface obeys specific non-Gaussian statistics of hights

Traditional roughness - trivial stochastic relief

Abrasive surface : PDF is close to Gaussian law







PDF is close to Gaussian - trivial stochasticity

Statistical property of the roughness can be changed by different plasma treatment.
Appropriative for drag reduction

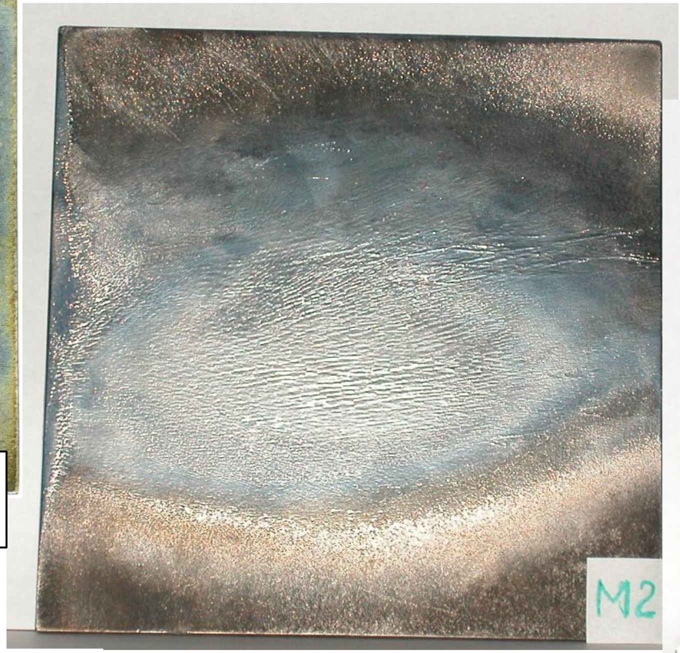


Plate models -top view

Plasma flow impact on the surface growth in a process of film deposition

Surface growth is very sensitive to fluctuations (even small) in deposited flow

Budaev,
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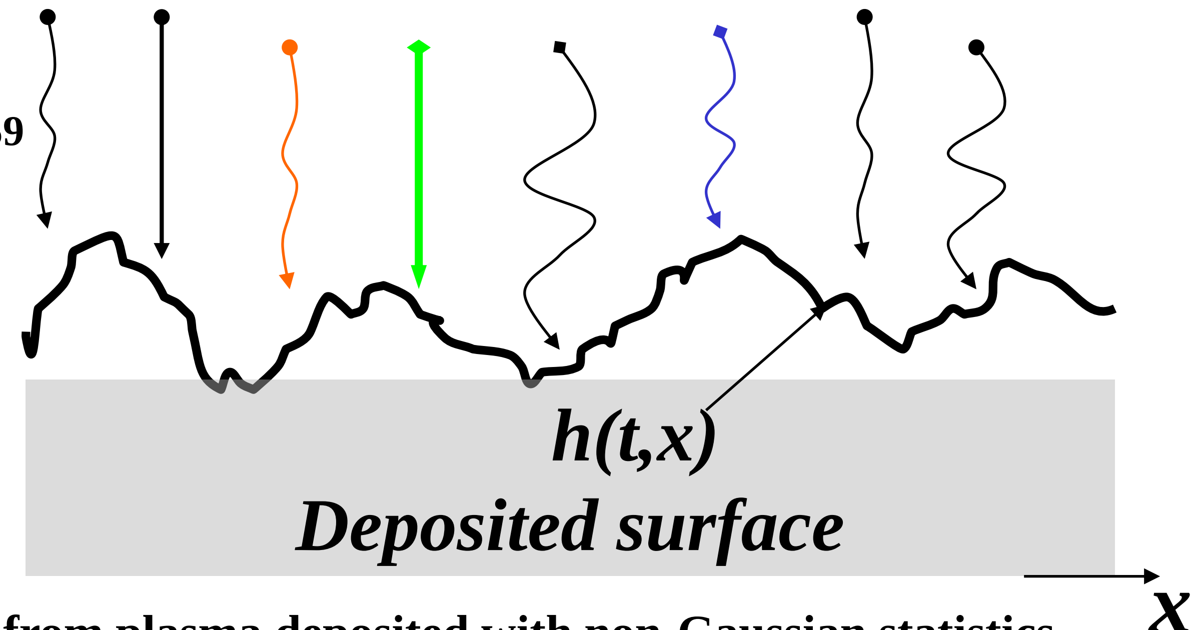
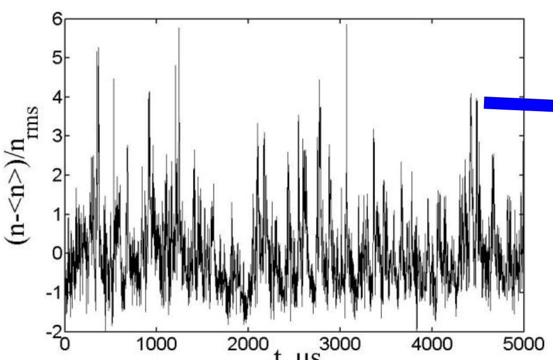
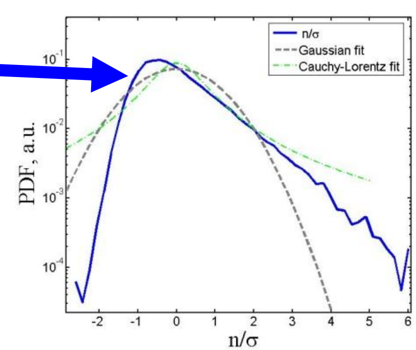


Turbulent flow from plasma deposited with non-Gaussian statistics



T-10



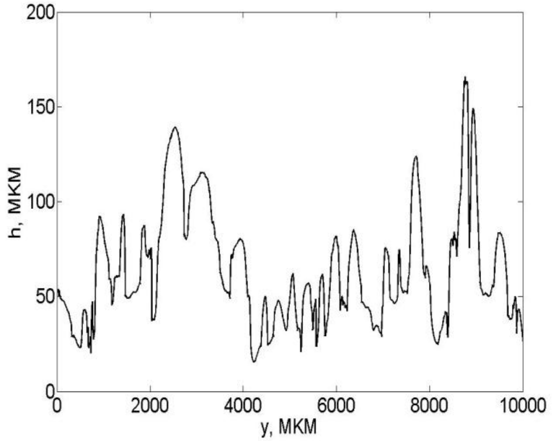
Fractal growth with bursty shape of relief-specific property of high temperature plasma

Fractal growth: competition of spikes growth and relaxation
Kardar-Parisi-Zhang (KPZ) Eq.

$$\frac{\partial h}{\partial t} = \eta(\vec{x}, t) + \Psi\left(h, \nabla h, \nabla^2 h, \ldots\right)$$

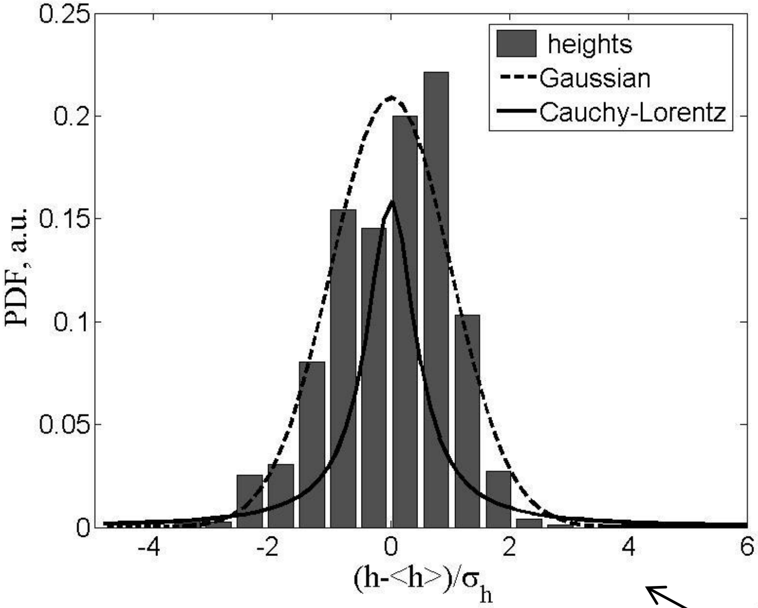
$$\frac{\partial h}{\partial t} = \eta(\vec{x}, t) + \nu \nabla^2 h + \frac{\lambda}{2}(\nabla h)^2$$

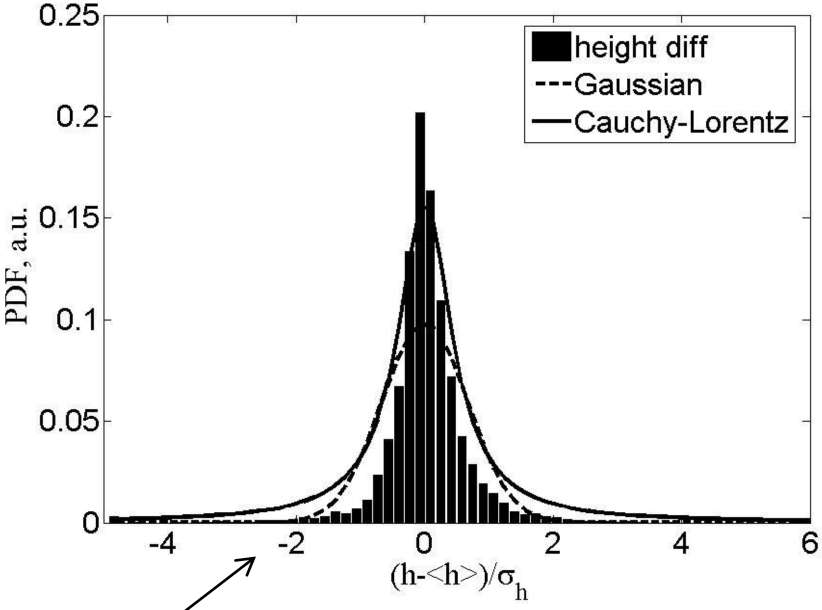
Noise ***$\eta(x,t)$*** ⇨ ***h(x, t)*** **– self-similarity (fractality) of hights**



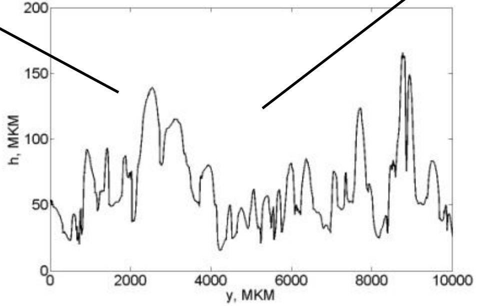
roughness~ $x^{\alpha}\Phi(t/x^{\alpha/\beta})$

Fractal surface of metal model after plasma treatment
Probability distribution function of relief heights : non-Gaussian





model №1



Experiments in wind tunnel T-36I

Comparative study of different roughness:

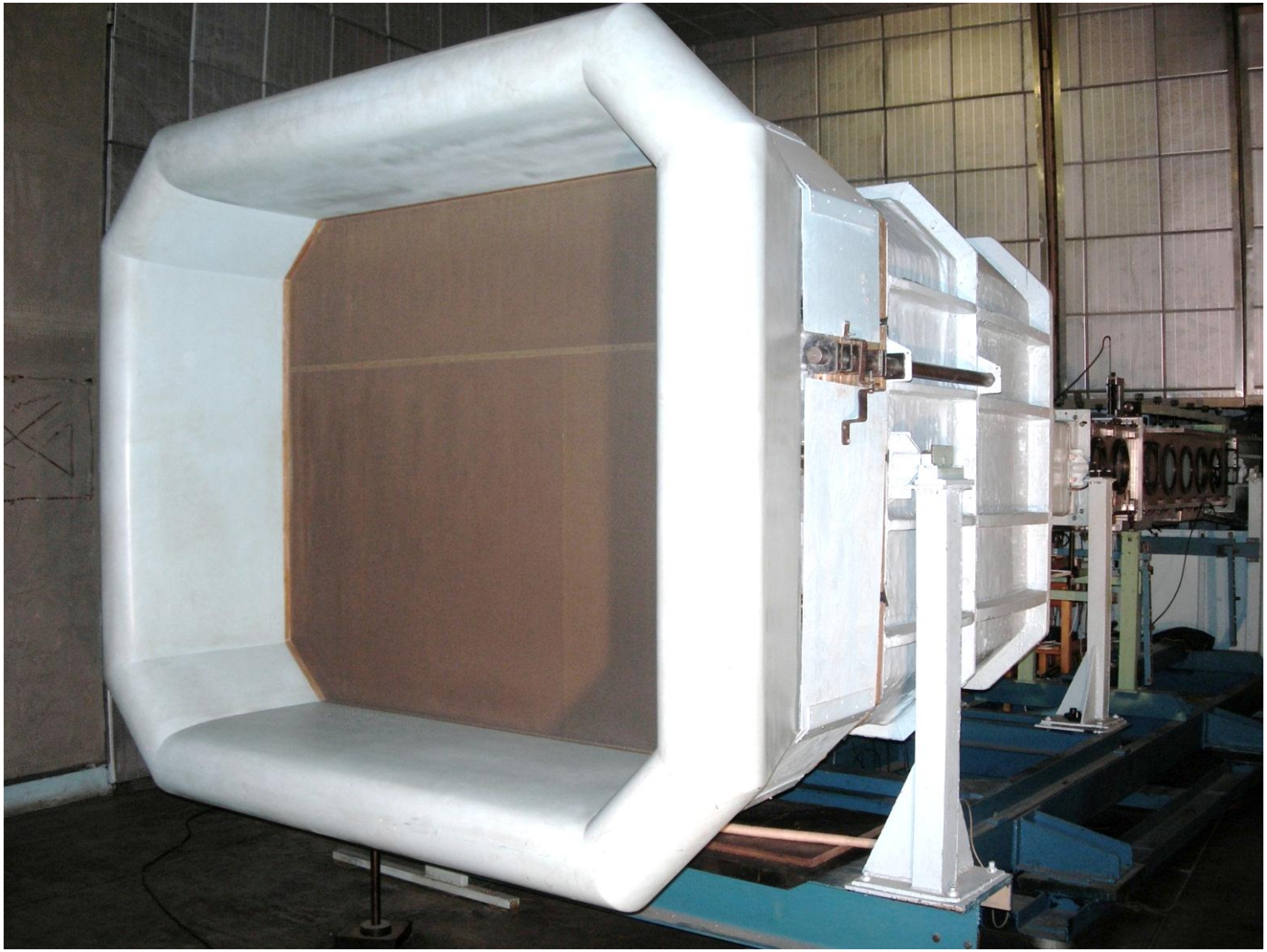
smooth, trivial roughness, fractal roughness

- **Model №1, fractal roughness , plate after high-temperature treatment in QSPA by heat load** 1.5 MJ/m^2
- **Model №2, fractal roughness , plate after high-temperature treatment in QSPA by 1 shot, heat load** 1 MJ/m^2
- **Model №3, fractal roughness , plate after high-temperature treatment in QSPA by 4 shots, heat load** 1 MJ/m^2
- **Glass model, smooth surface**
- **Abrasive surface , plates** PS11 C industrial KLINGSPOR, CSi– P120 и P280 grains of 120 μм
- **Stainless steel plate, industrial rolling, original surface before plasma treatment**

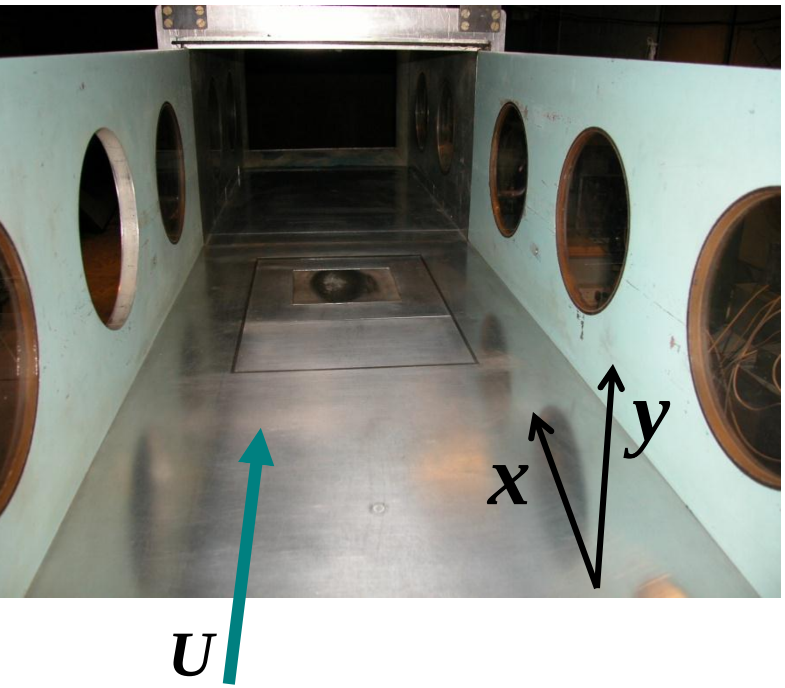
Wind tunnel T-36I in Zhukovsky Institute (TsAGI-ЦАГИ), linear flow type

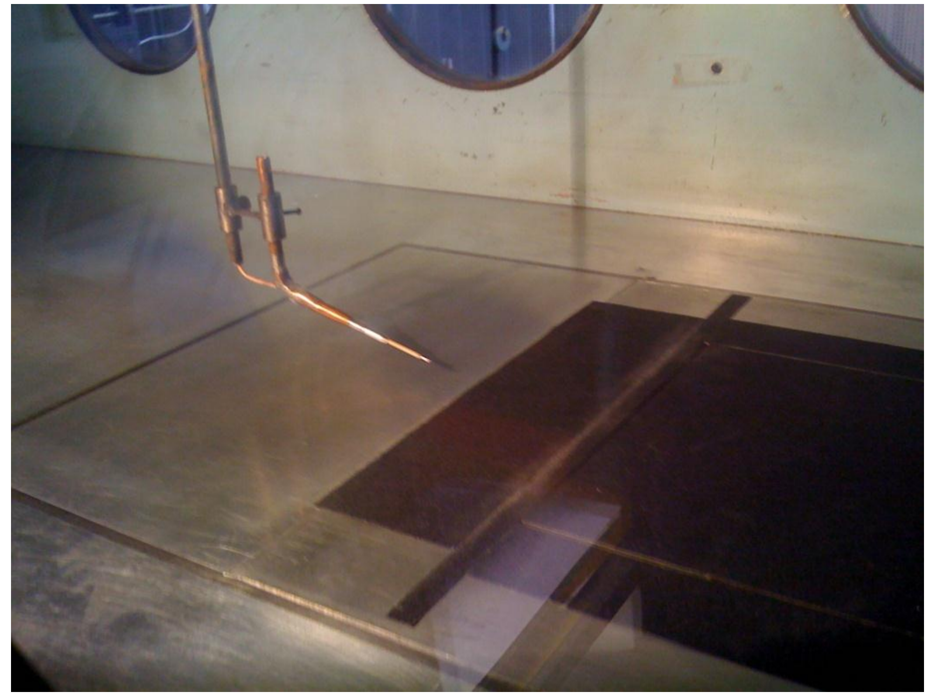
length 2600 mm, size 500x350 mm.

flow 5 – 50 m/s (Re_1 from ~$0.2*10^6$ to ~ $4*10^6$), turbulence level 0.06 %.



Fractal model inside the wind tunnel T-36I



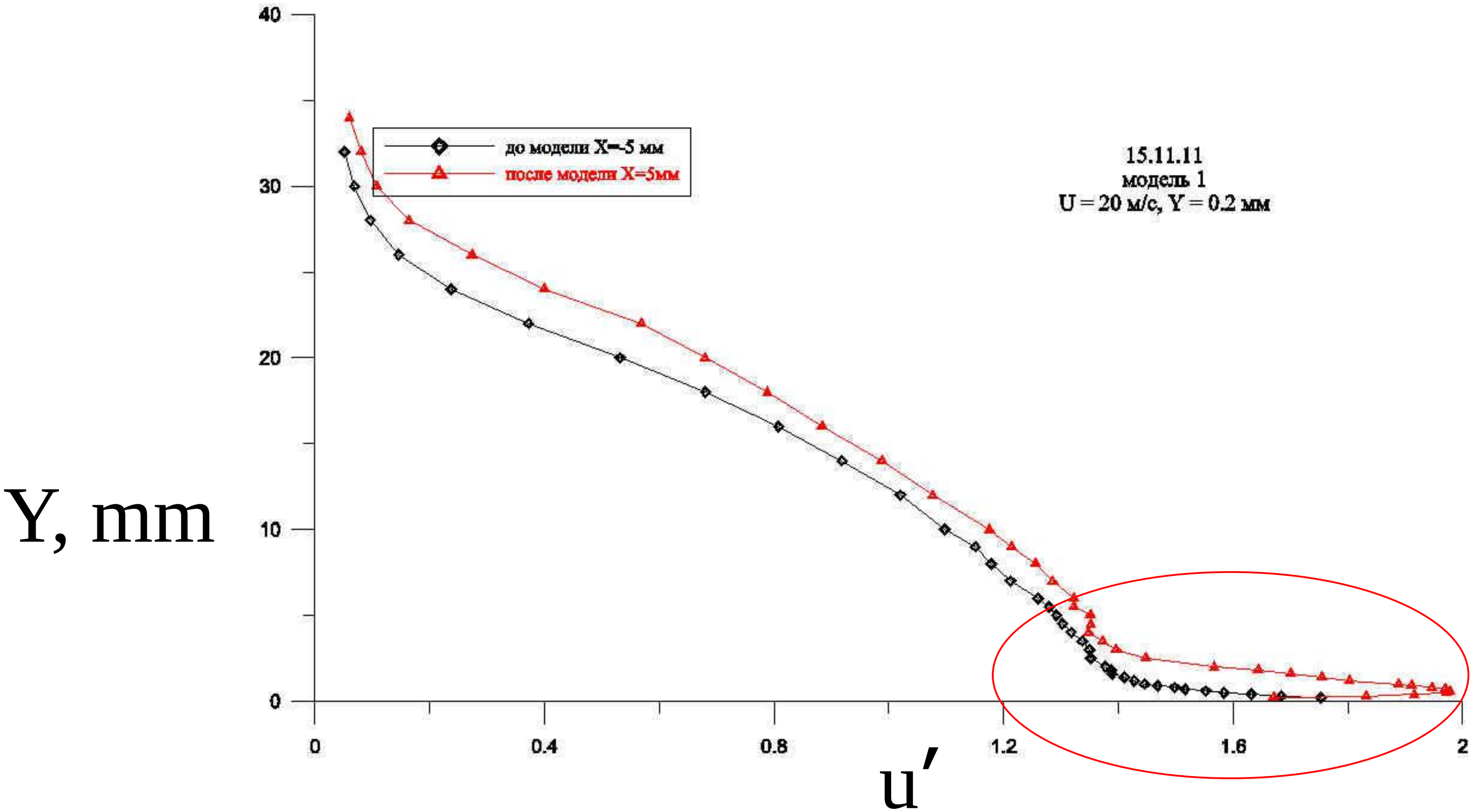


Model: fractal surface plate of 160 × 160 mm , on the bottom bound of the flow .
Turbulent flow .
Averaged flow velocity U=10,20,30 m/s, $Re_l = 5\times10^5 - 3\times10^6$.
Measurements : hot wire, drag coefficient

Turbulent boundary layer thickness in T-36I

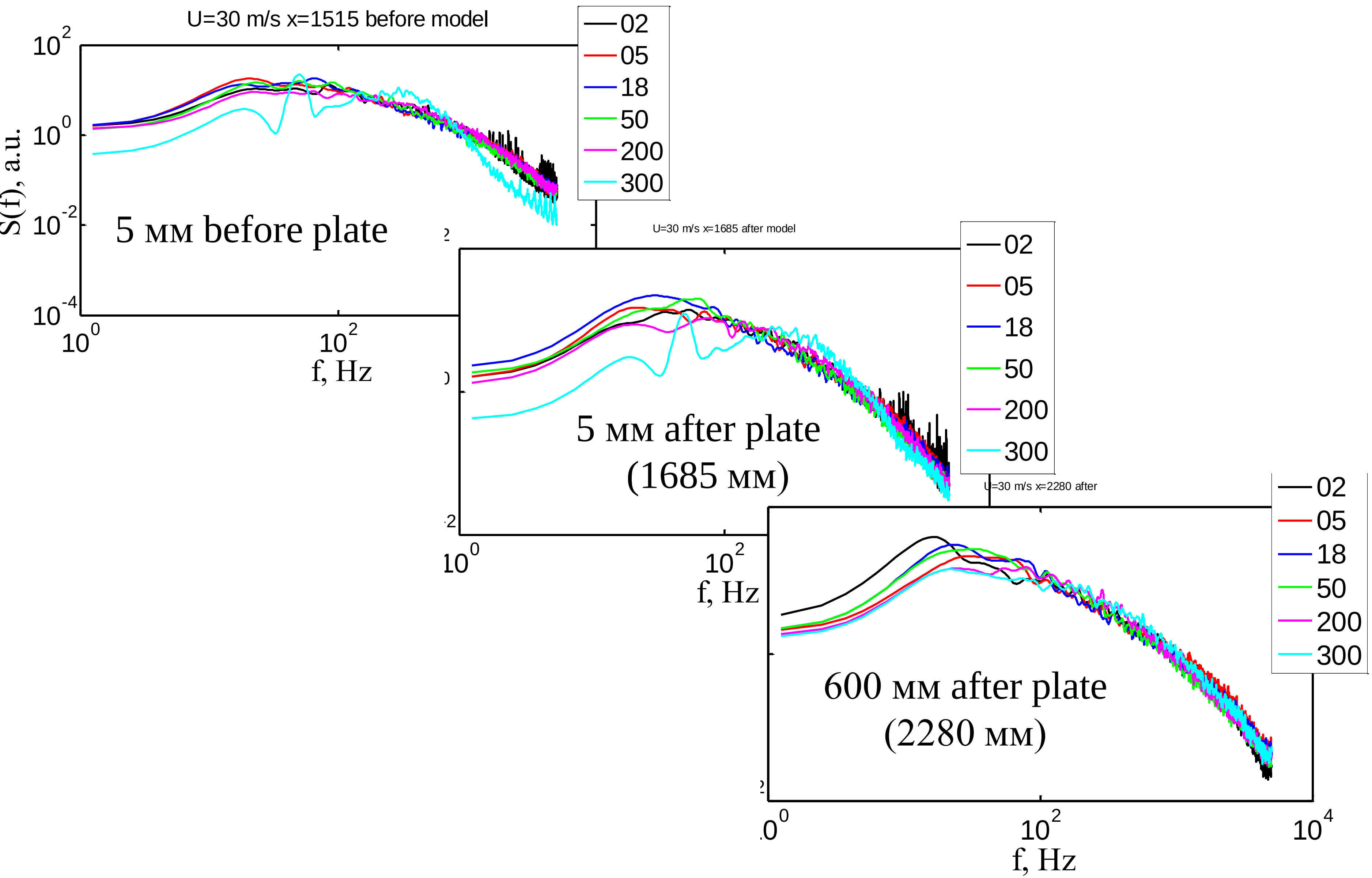
x from starting point	10 m/s	20 m/s	30 m/s
1515 mm 5 mm for the model	25.75 mm	24.25 mm	23.34 mm
1685 mm 5 mm after the model	27.75 mm	25.50 mm	25.00 mm
2280 мм 600 mm after the model	38.24 mm	33.34 mm	32.60 mm

velocity <u′> vs. Y, distance to plate

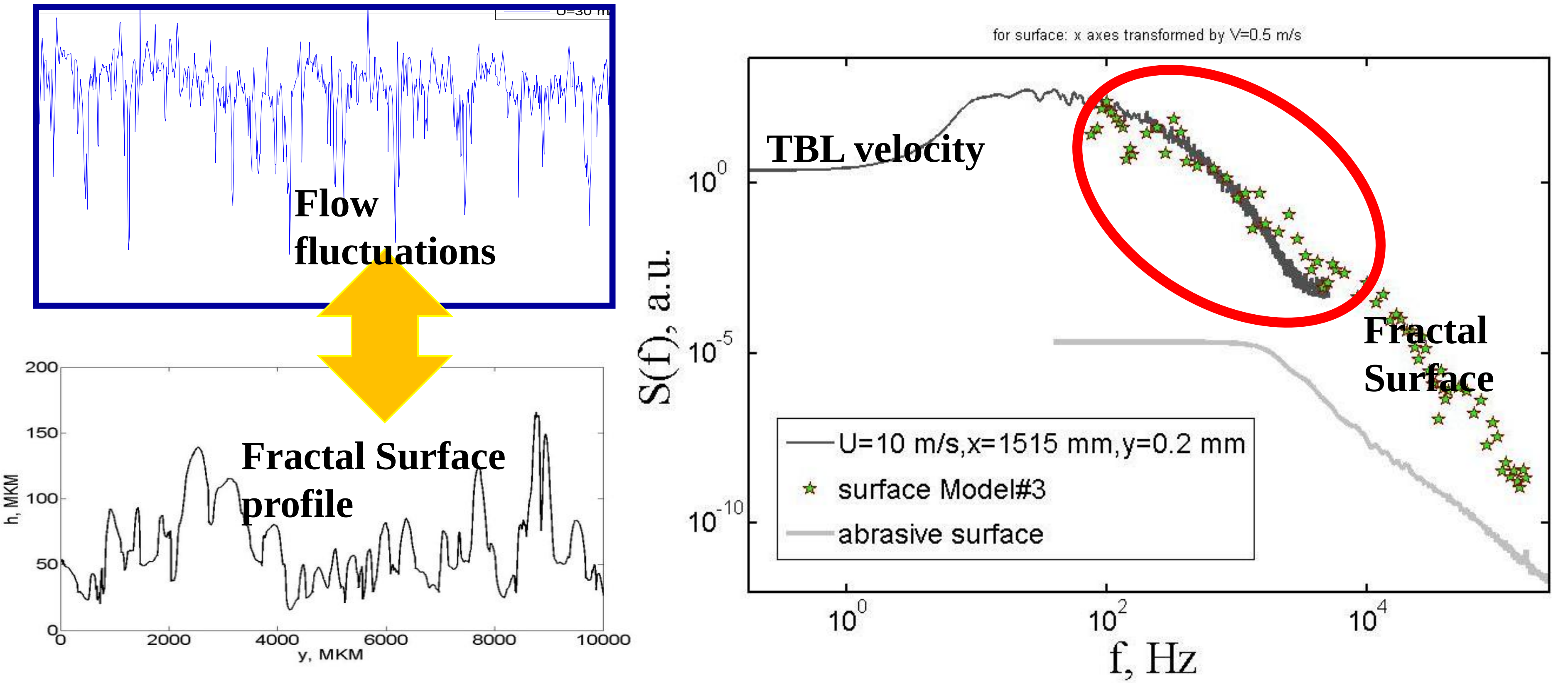


Fractal surface impact on the TBL velocity profile

Fourier spectrum: reconstruction of TBL by effect of fractal surface

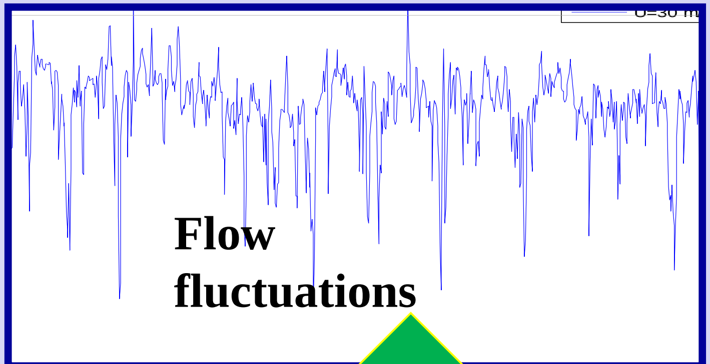


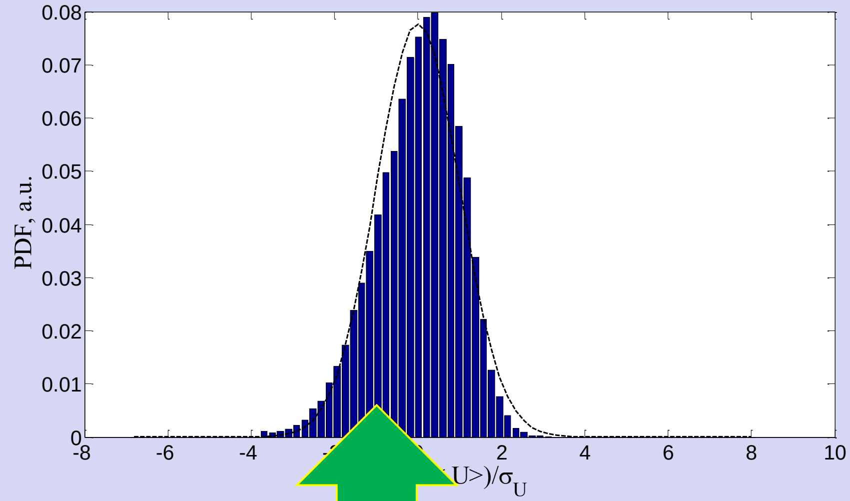
TBL velocity spectrum and fractal surface relief spectrum are identical – power laws

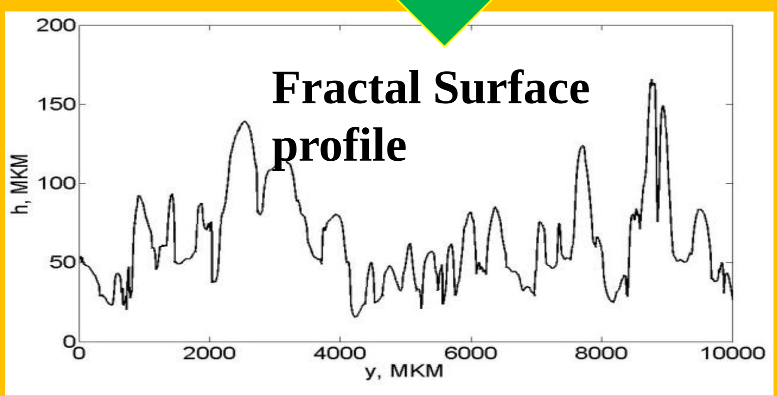


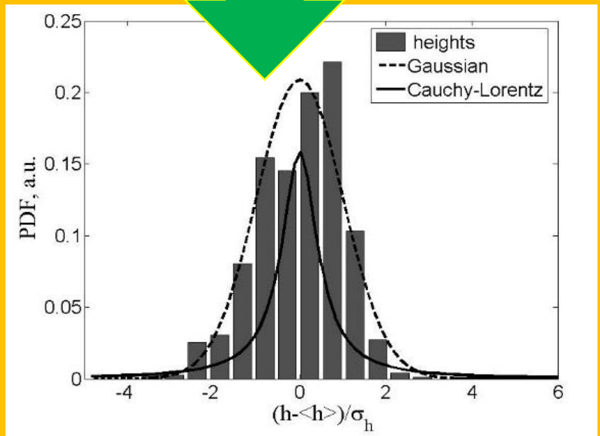
Fractal surface effect on TBL due to the similarity of it's spectrum with flow spectrum . Abrasive - does not!

Statistics of TBL velocity and fractal surface relief are identical: effective interaction and dumping of drag









Fractal surface affects due to the similarity of it's statistics with flow spectrum . Abrasive - does not!

Drug C_f

$$F = \frac{1}{2}\rho u^2 C_f A$$

A- area, ρ - density , *u* flow velocity.

For smooth C_f <<1,

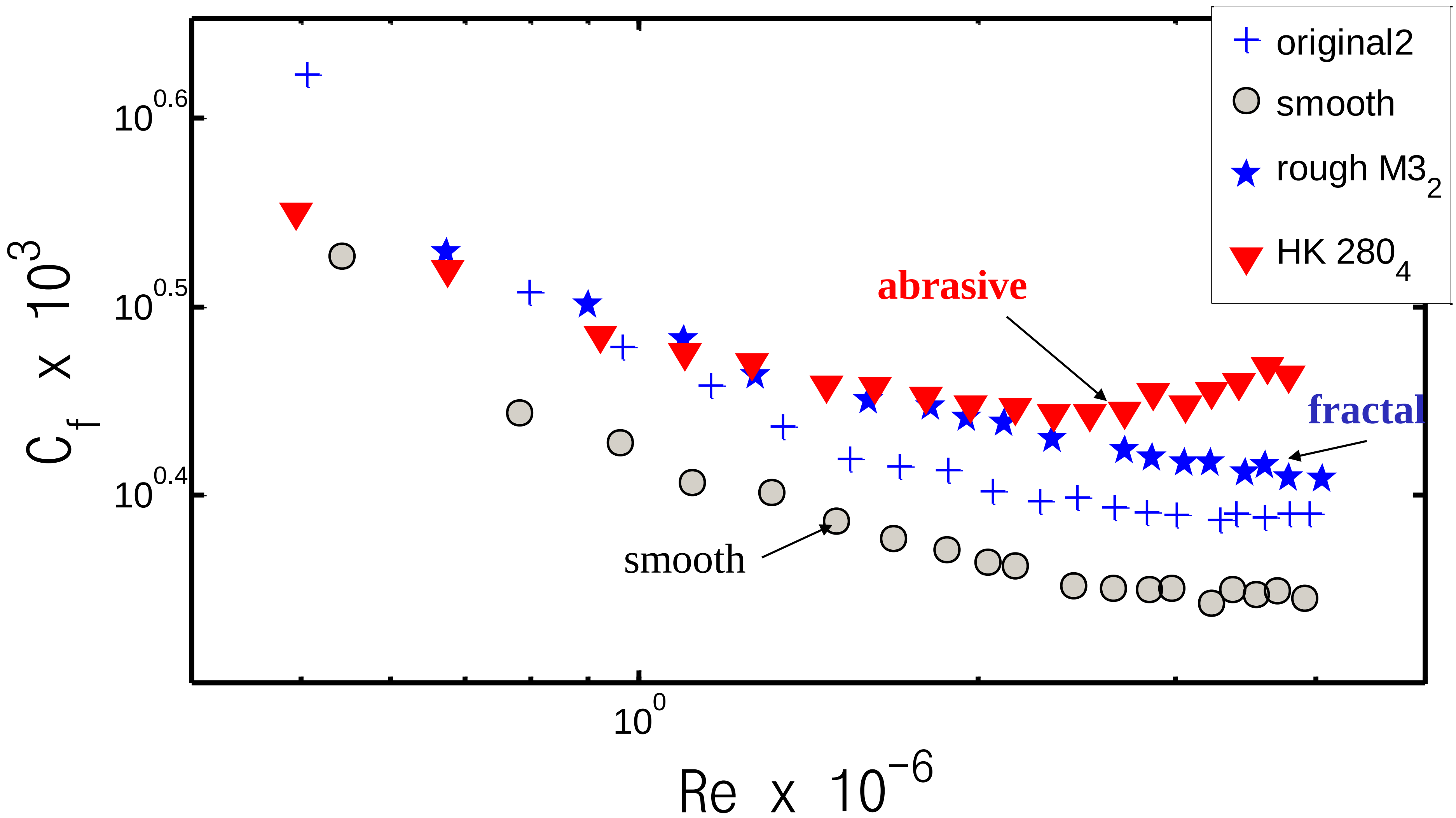
For rough C_f =>1

Prandtl law for smooth plate in turbulent flow :

$C_f = 0.074\ (Re_l)^{-1/5}$

for $5 10^5 < Re_l < 10^7$.

Drug C_f for smooth, abrasive and fractal surface



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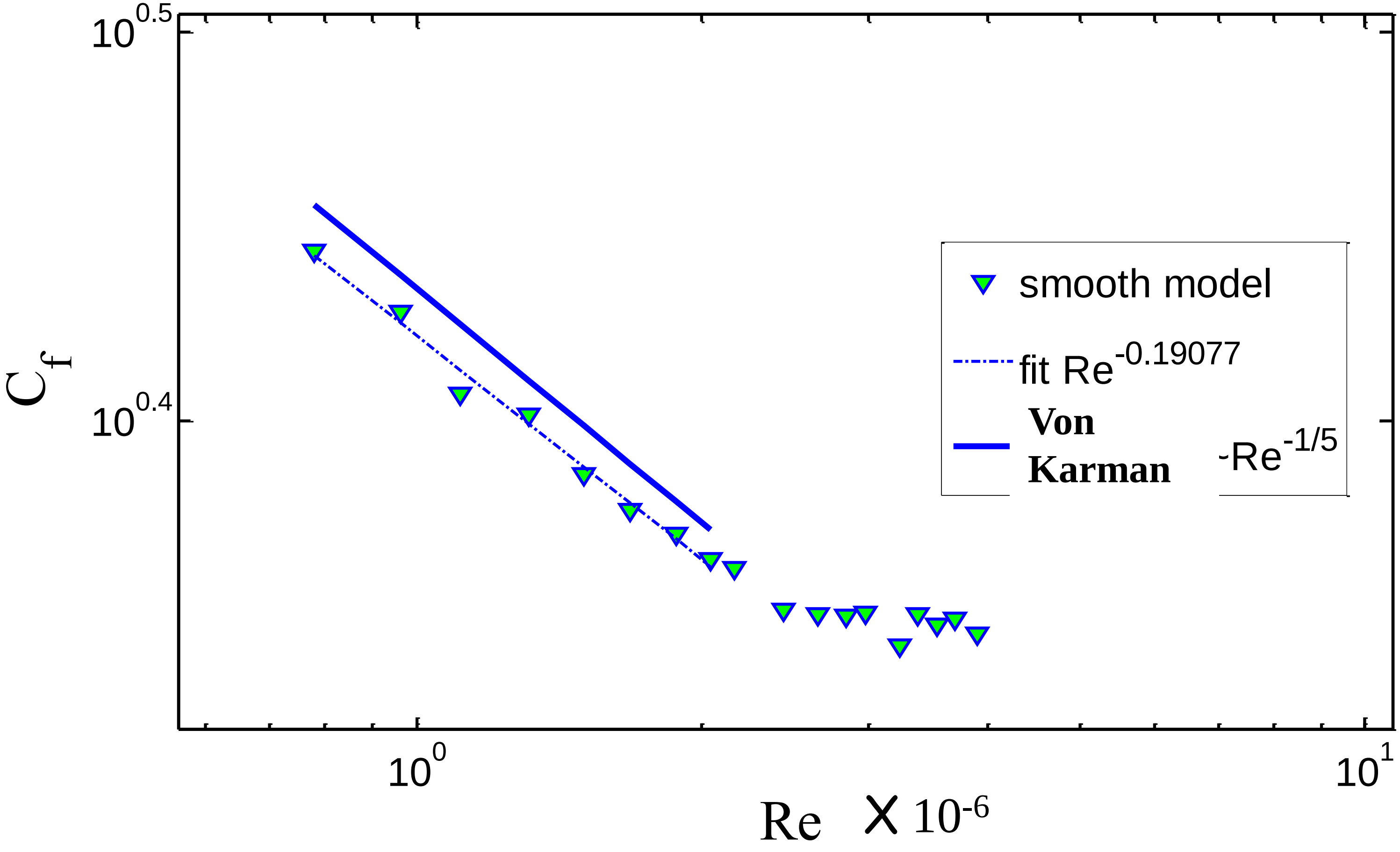
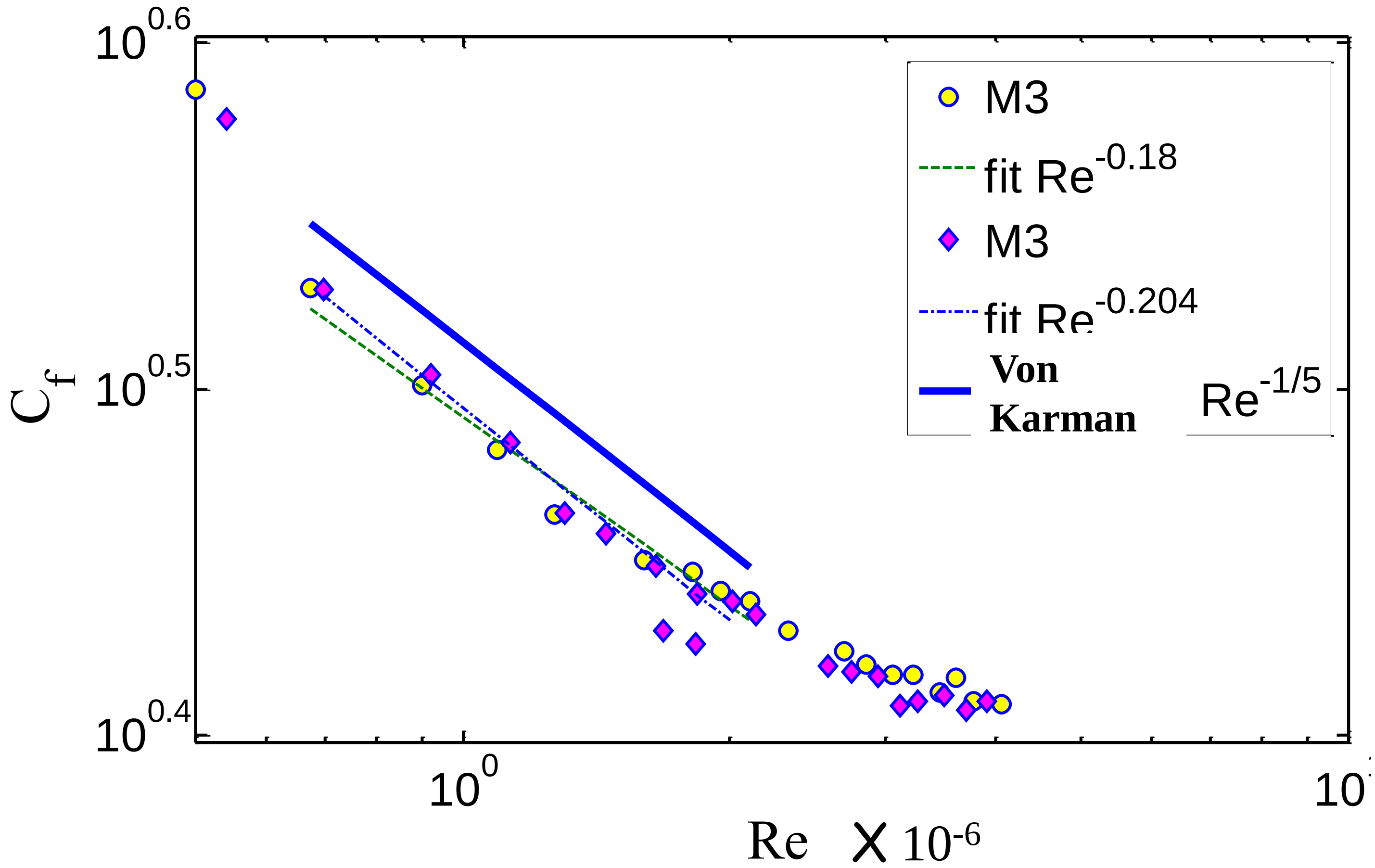
Experiments in T-36I
Smooth glass, drag $C_f \sim Re^{-1/5}$

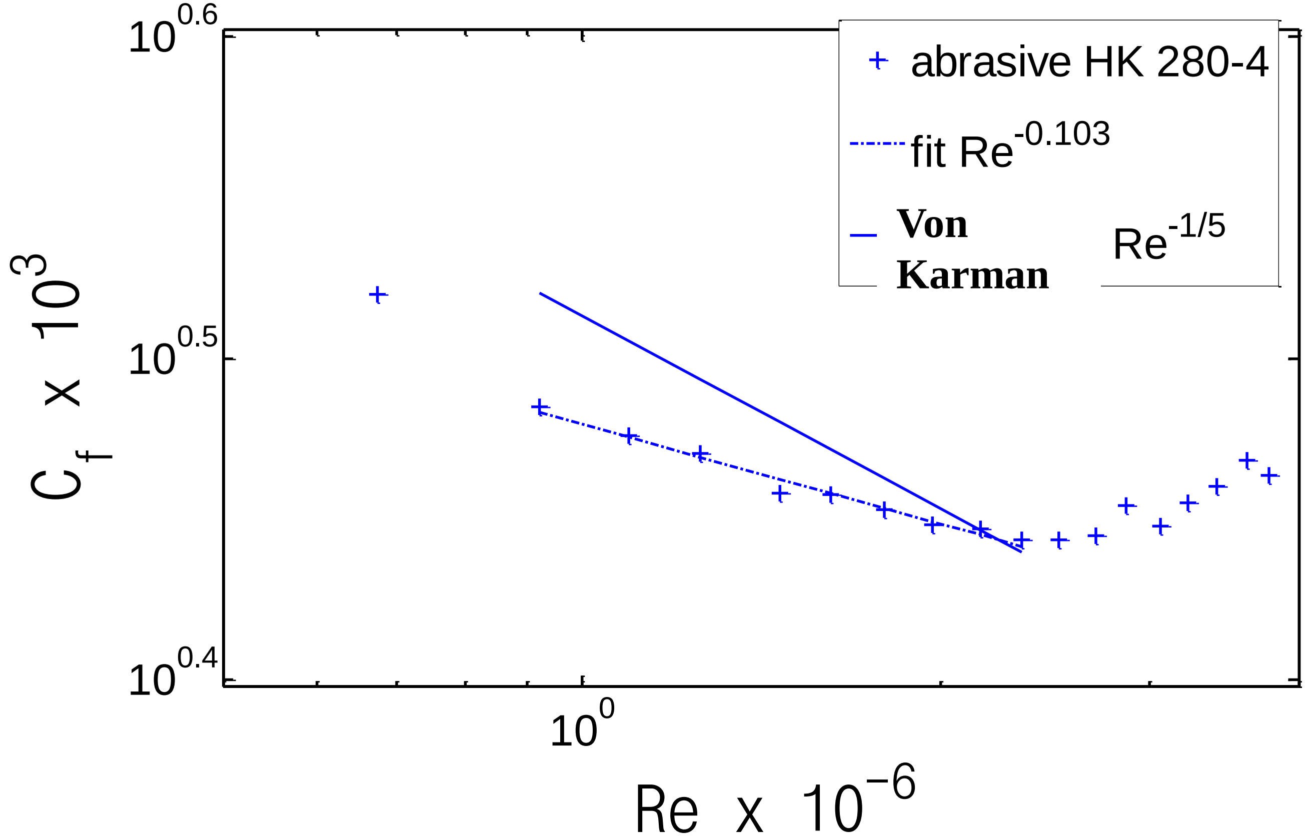


Experiments in T-36I
Drag: Fractal surface M3



Fractal surface is close to theoretical prediction for smooth plate $C_f \sim Re^{-1/5}$

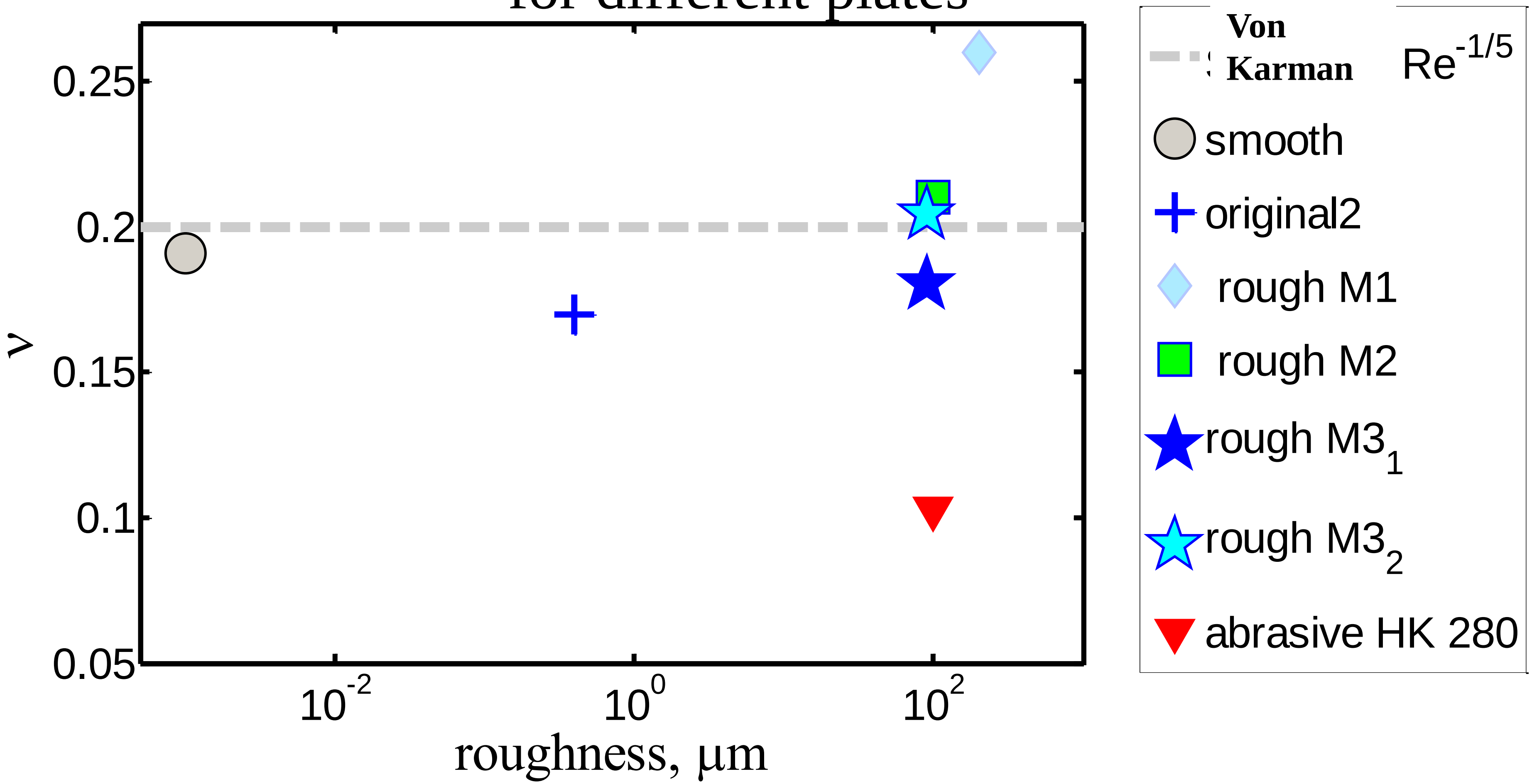
Experiments in T-36I
Abrasive surface: drag $C_f \sim Re^{-0.103}$



Scaling for abrasive is far from scaling for fractal surface C_f

Experiments in T-36I

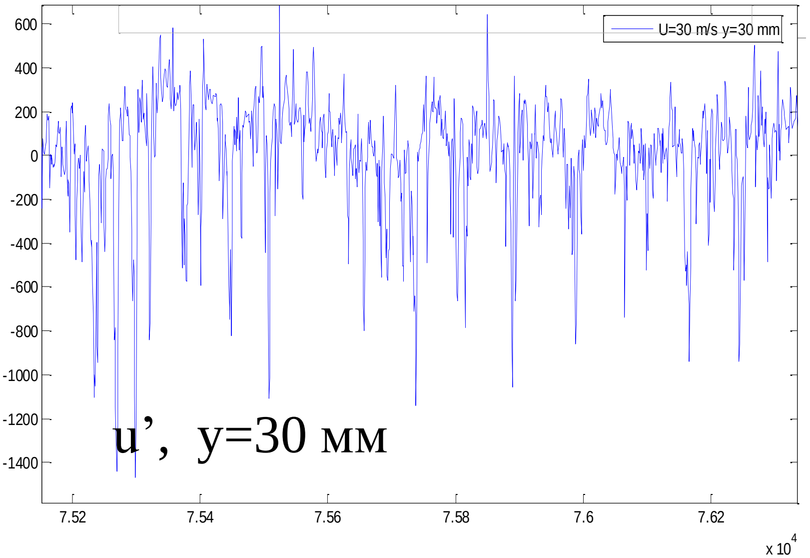
Index ν of drag coefficient scaling $C_f \sim Re^{-\nu}$ for different plates

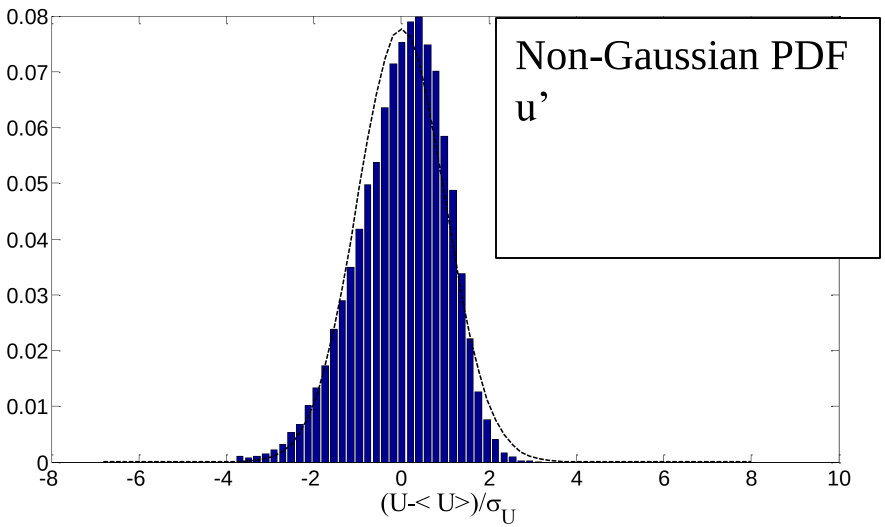


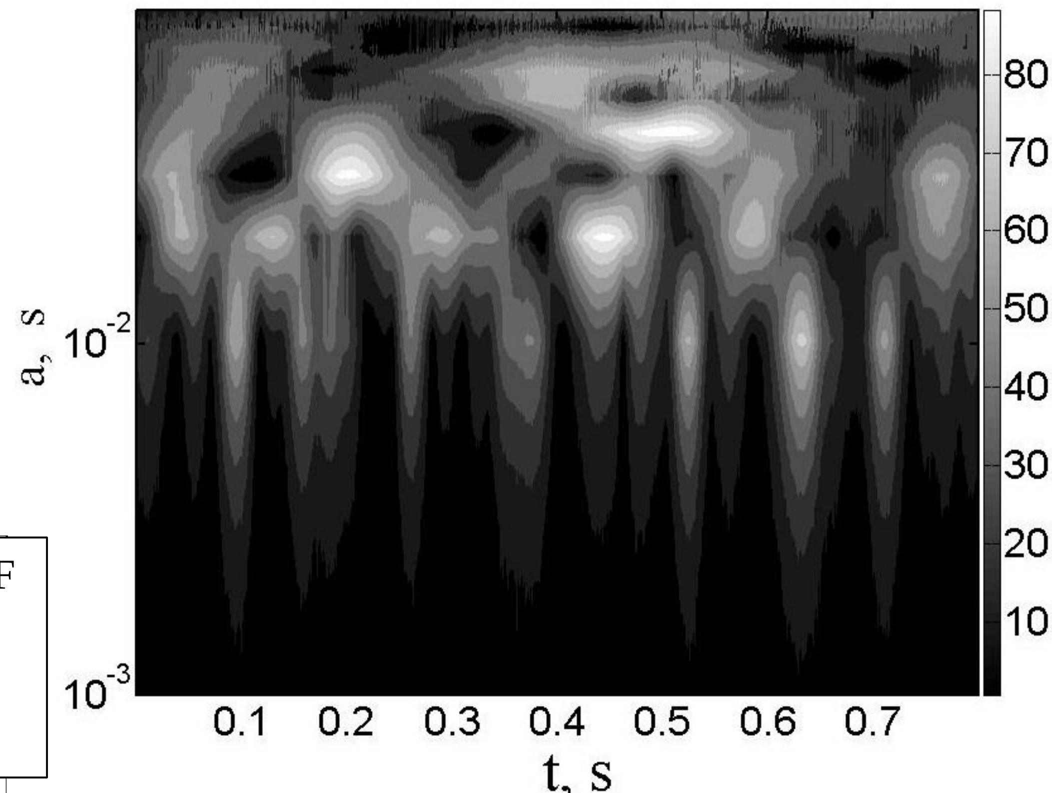
scaling index ν for fractal surfaces is close to smooth plate $C_f \sim Re^{-1/5}$

Fractal surface leads to the change of intermittency in TBL

Intermittency in turbulent boundary layer (TBL) Experiments in T-36I







velocity

U=20 m/s, y=2,5 mm, x=1515 мм (before plate)

Intermittency and multifractality of TBL
Scale invariance: a feature of turbulence

Navier-Stokes equations are invariant with respect to the scale transformation:

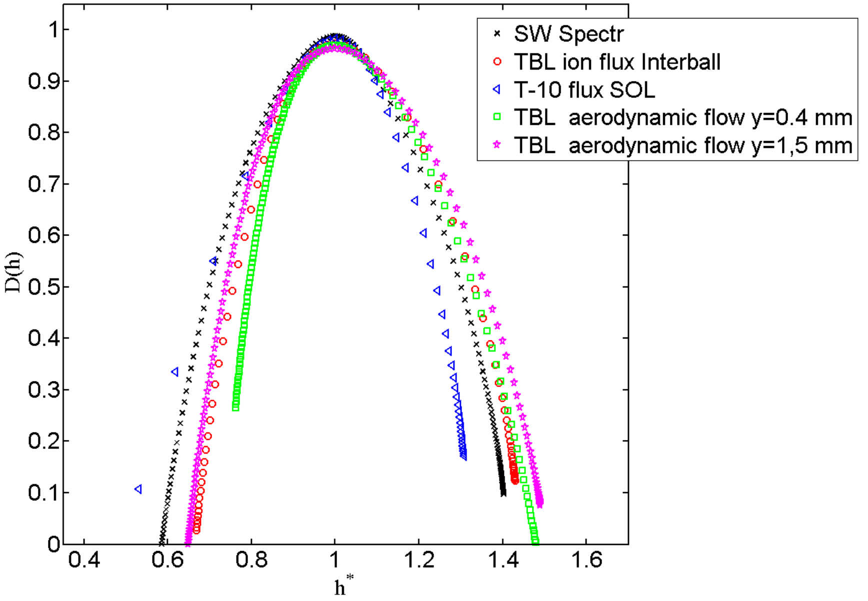
$$t, \vec{r}, \vec{u} \rightarrow \lambda^{1+h} t, \lambda \vec{r}, \lambda^{-h} \vec{u}$$

$$\lambda^{-2h-1} \partial_t \vec{u} + \lambda^{-2h-1} \left[(\vec{u} \nabla) \vec{u} + \rho^{-1} \nabla p \right] = \nu \lambda^{-h-2} \Delta \vec{u}$$

For viscosity ν = 0 : any h.

For $\nu \neq 0$: each fluctuation *h* at scale *l* is weighted with a probability distribution $P_h(l) \sim l^{\,3-D(h)}$.

Fractal dimension D(*h*) of the set for which $\delta u_l \sim l^h$



Multi-scaling (multifractality)

Approximation of experimental PDF by functions : very difficult problem

Alternative is to describe a non-homogeneity vs. scale:

moments of PDF (structure functions) is a mean to investigate turbulence:

$$S_q(\tau) = \left\langle \left(X(t) - X(t+\tau) \right)^q \right\rangle$$

$\langle \ldots \rangle$ - ensemble averaging. $X(r,t)$ – experimental signal: υ, n, B

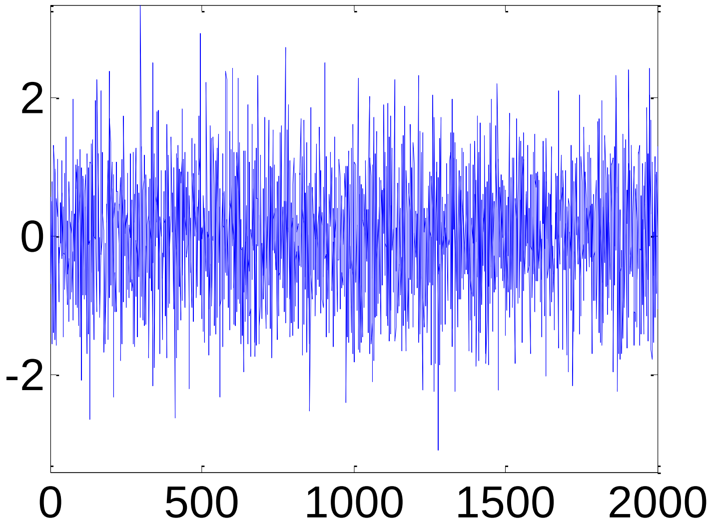
For a Gaussian ensemble $S_q(\tau) \sim \tau^{q/3}$ (Kolmogorov's)

Intermittency is quantified by $S_q(\tau) \sim \tau^{\zeta(q)}$ (non-Gaussian)

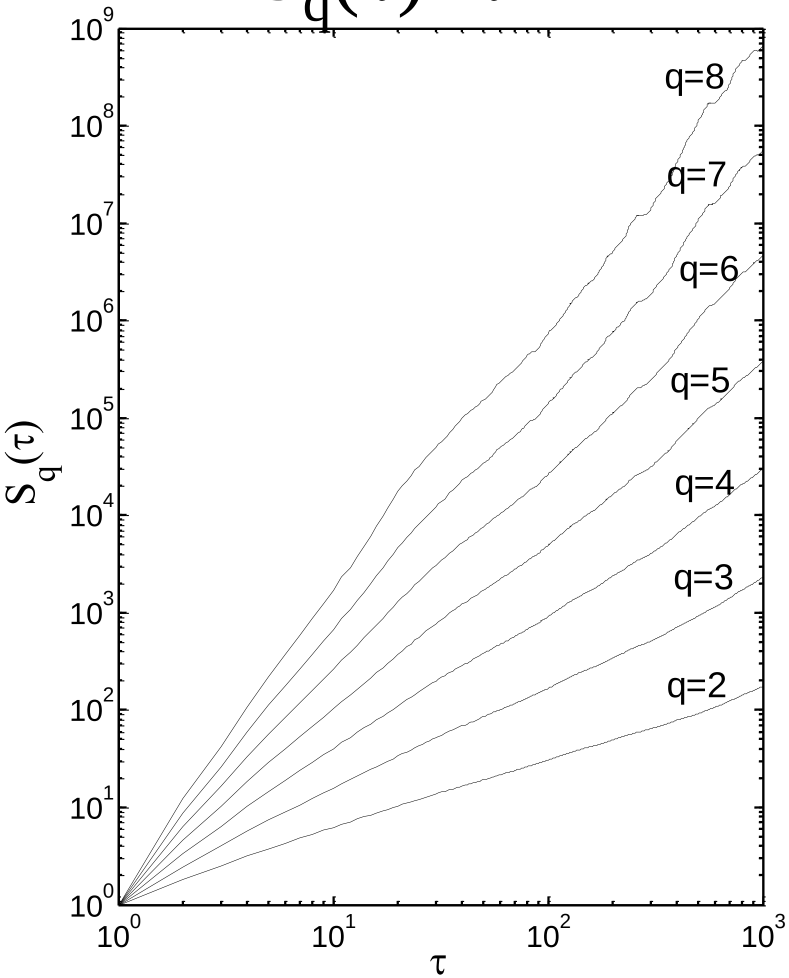
From symmetry of Navier-Stokes eqs. exact result : $\zeta(3)=1$

Structure function of fractional Brownian motion – simulated random signal with Gaussian PDF

Brownian signal

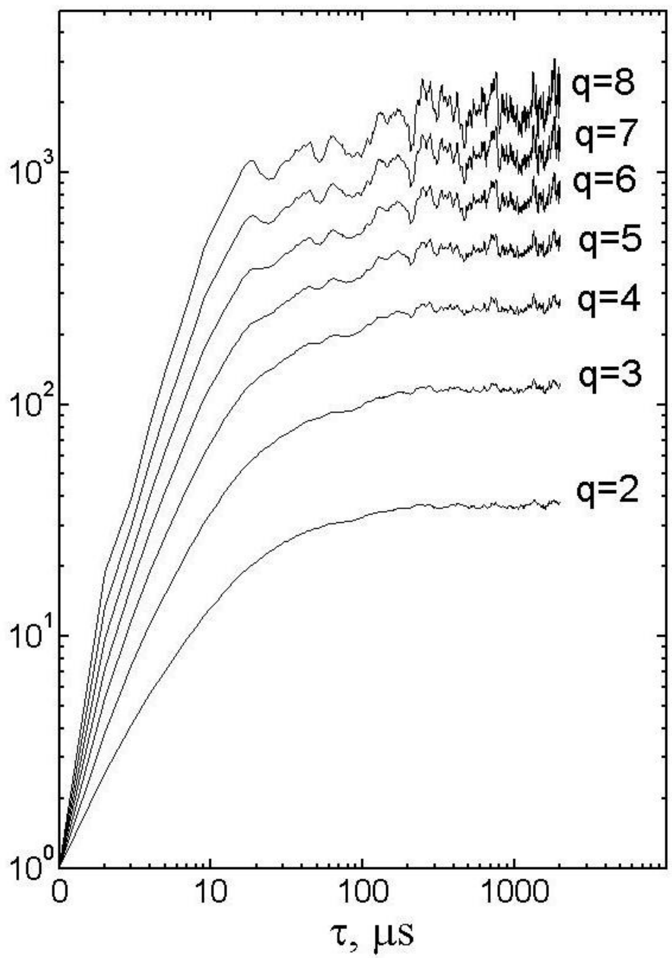


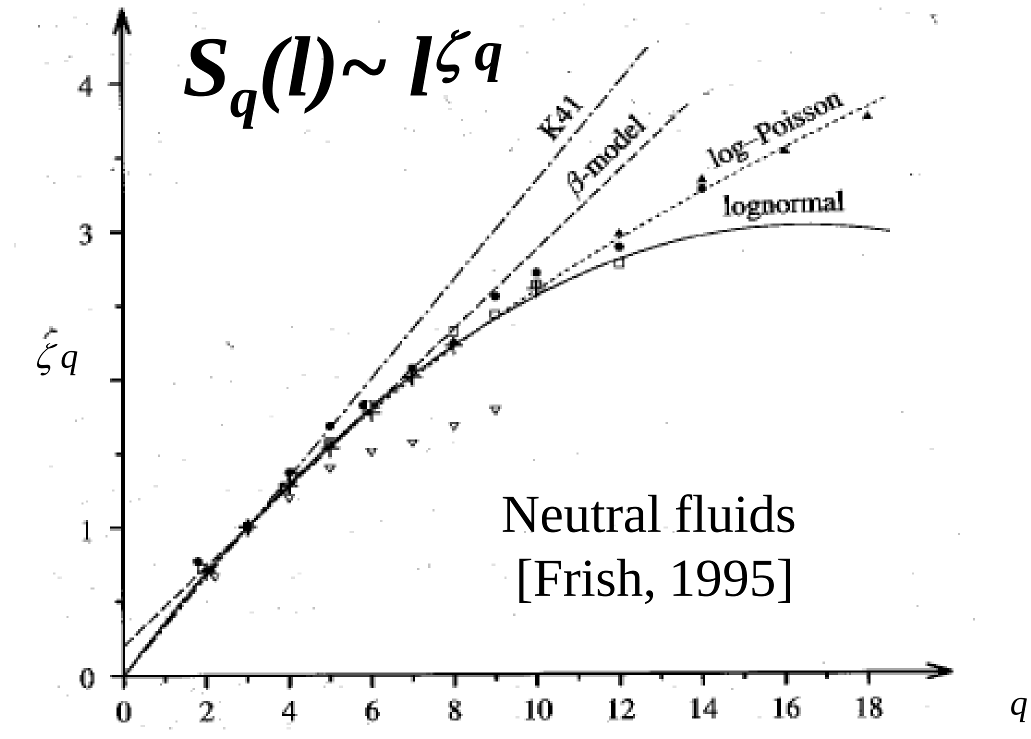
$$S_q(\tau) \sim \tau^{q/3}$$



Structure function of experimental data - intermittency

$$S_q(\tau) = \left\langle \left(X(t) - X(t+\tau) \right)^q \right\rangle \qquad S_q(\tau) \sim \tau^{\zeta(q)} \qquad S_q(\tau) = S_3(\tau)^{\zeta_q/\zeta_3}$$

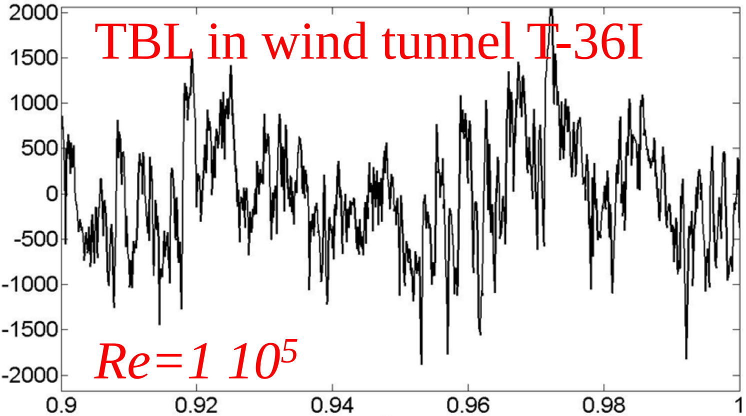


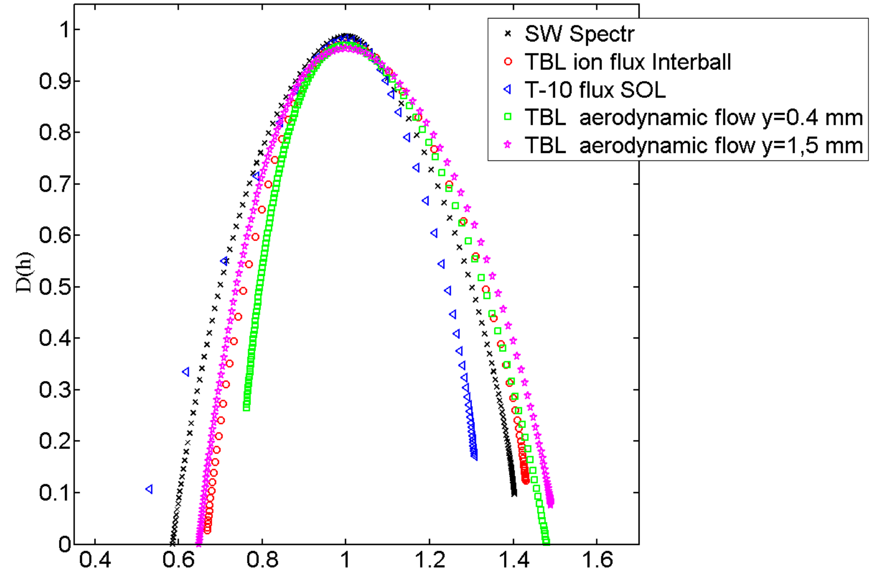


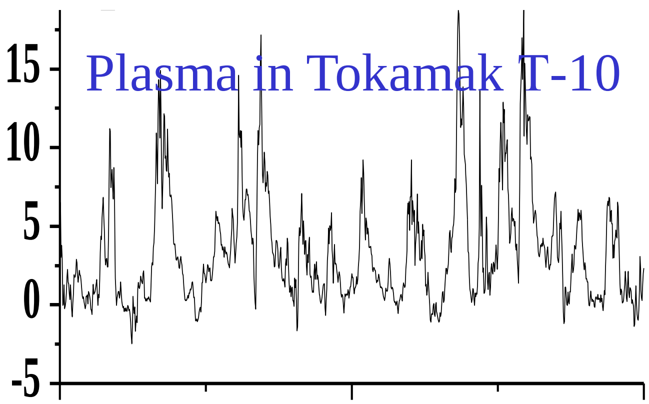
q

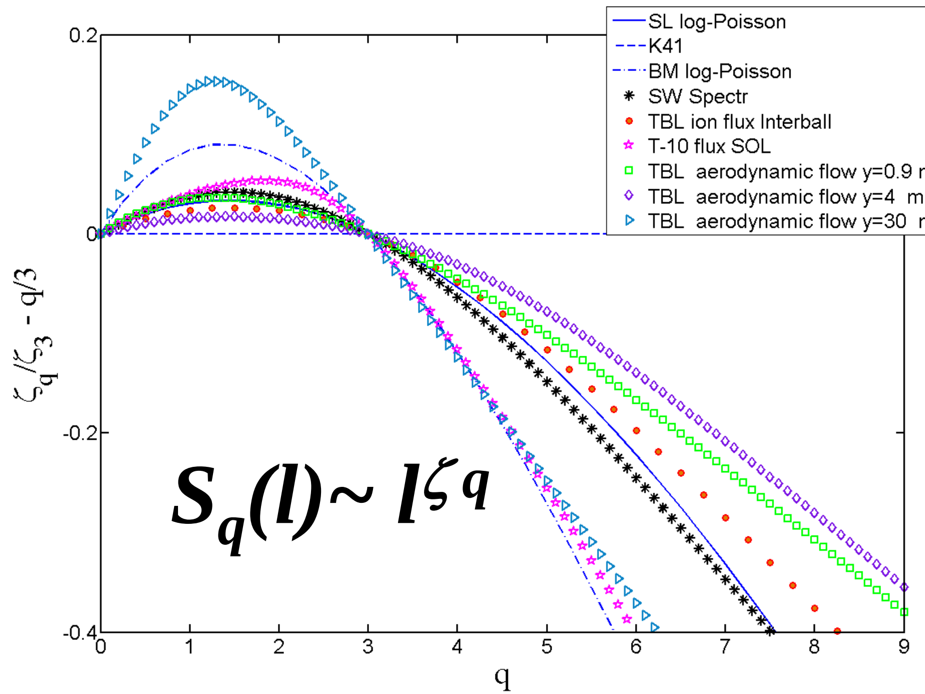
Intermittency - nonlinear dependence ζ(q)

Universality of intermittency in neutral fluids and plasma TBLs





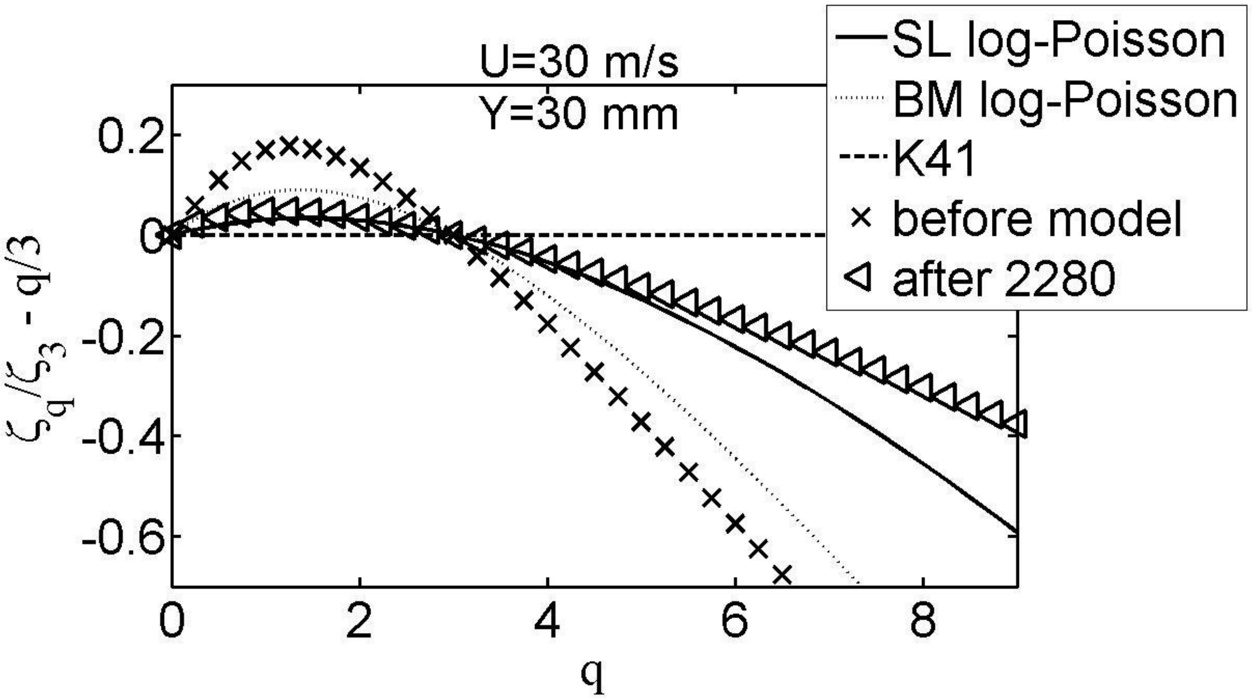


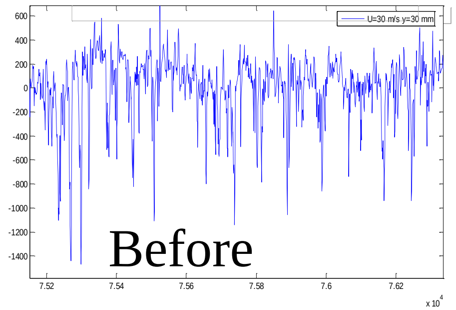


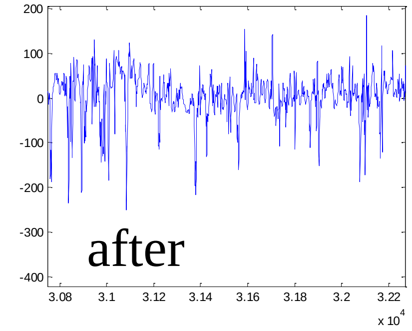
Intermittency, multifractality
Log-Poisson statistics

В. П. Будаев, С. П. Савин,
Л. М. Зеленый, УФН, 181,9,905, 2011

Fractal surface effect on TBL: Change of structure function scaling







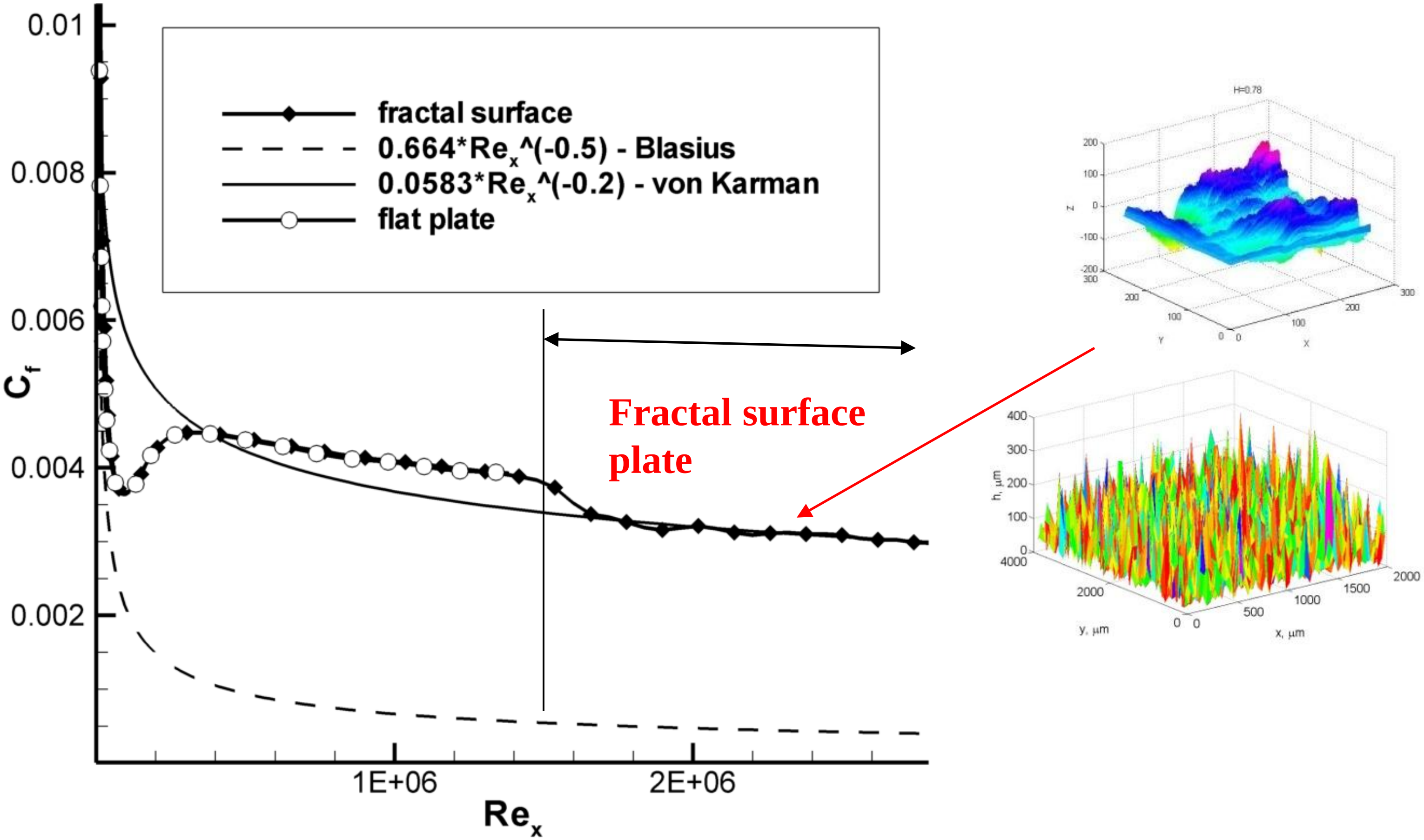
$$S_q(\tau) = S_3(\tau)^{\zeta_q/\zeta_3}$$

$$S_q(\tau) = \left\langle \left(\delta_\tau u(\vec{r},t)\right)^q \right\rangle \sim \tau^{\zeta(q)}$$

$$\delta_\tau u(\vec{r},t) = \left[u(\vec{r},t) - u(\vec{r},t+\tau)\right]$$

Change of intermittency

Numerical simulation of the TBL over the fractal surface



Drag coefficient C_f

Experimental observations are in agreement with the numerical simulation of the TBL over the fractal surface. Numerical simulation based on the 3D Reynolds equations and the *Spalart–Allmaras model* solved by the finite volume method have **shown a reduction of the c_f over the fractal surface** as compared with no reduction for the abrasive surface (with the Gaussian statistics of heights).

SUMMARY

Plans:

Cone with fractal surface will be tested in hypersonic flow

Cylinder model with fractal surface will be investigated in wind tunnel

The **numerical simulation** of the TBL over the fractal surface

Problems:

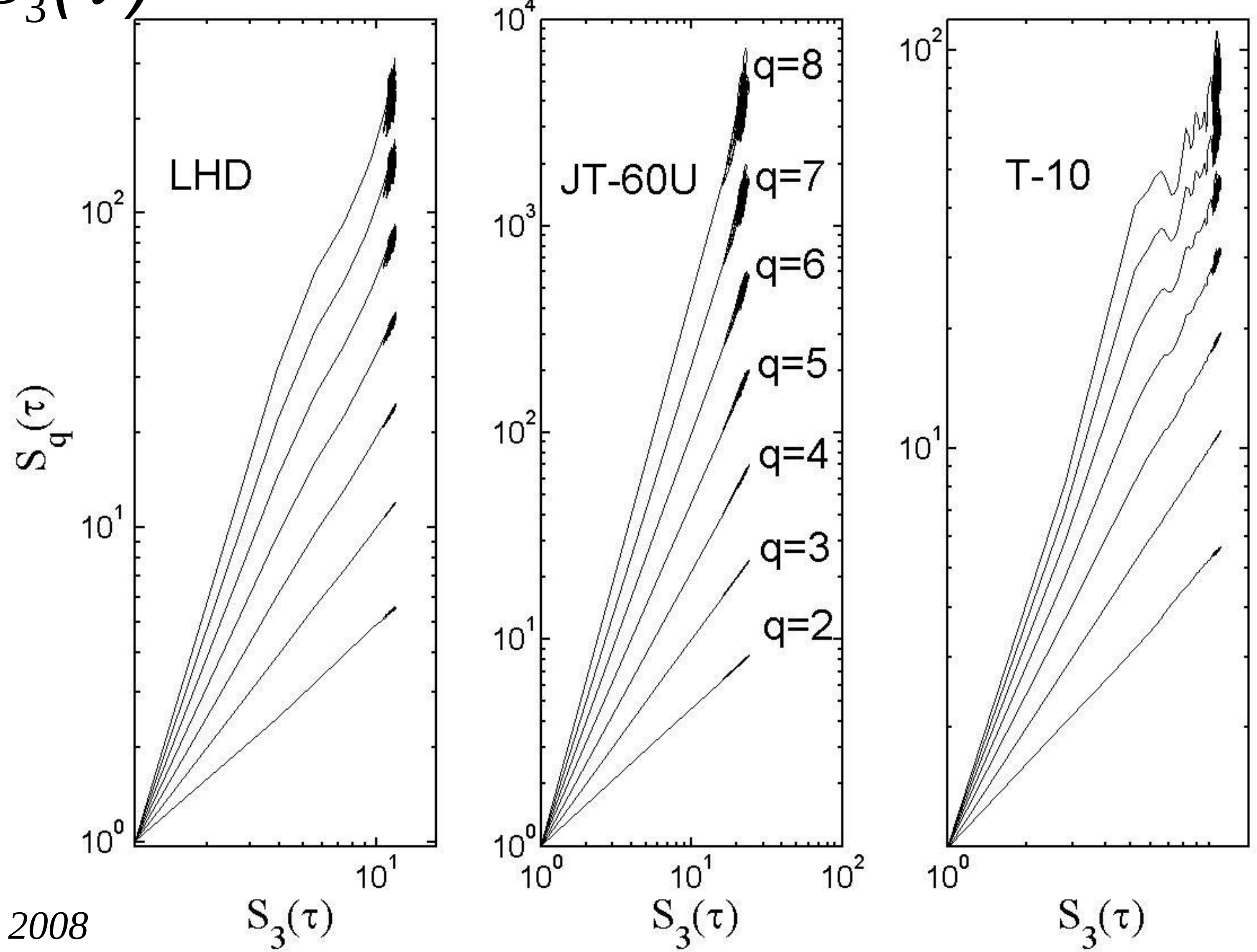
PIV measurements are needed

Λ-structure dynamics has to be investigated (effect of fractal surface on large-scale structures)

Thank you!

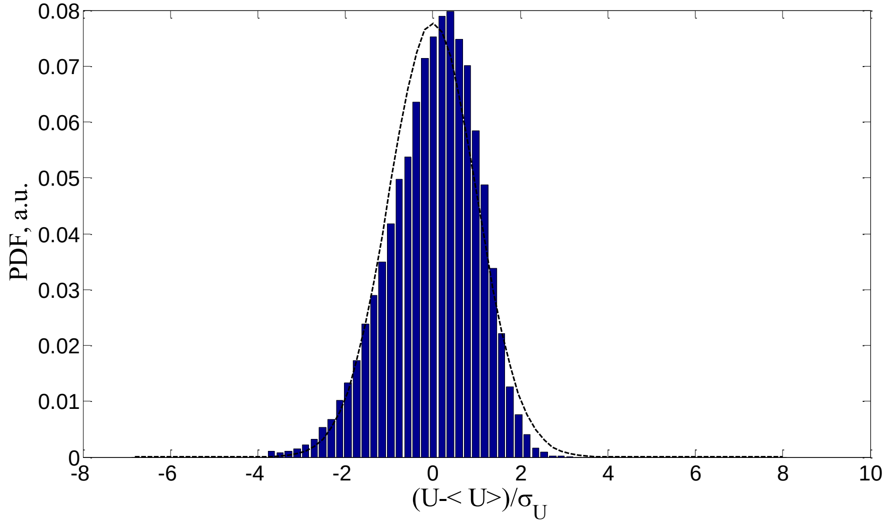
Plasma edge: Extended Self-Similarity
Generalized Scale Invariance on a scale >1 ms

$$S_q(\tau) = S_3(\tau)^{\zeta_q / \zeta_3}$$

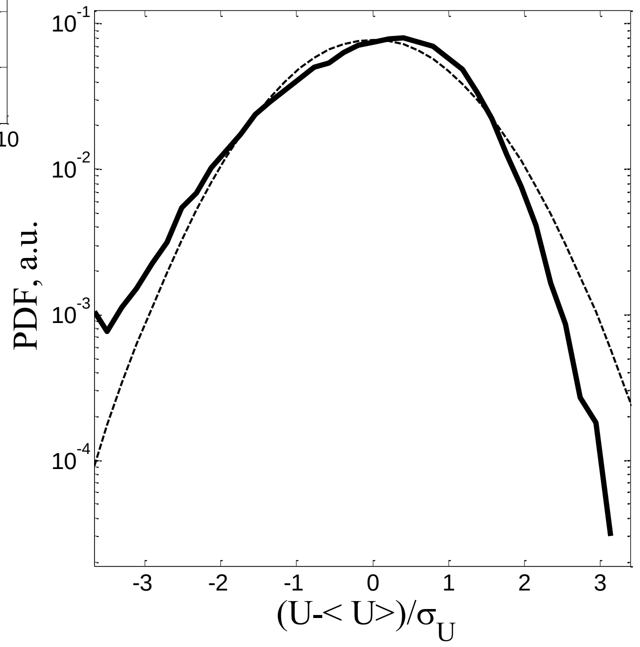


Budaev e a PFR 2008

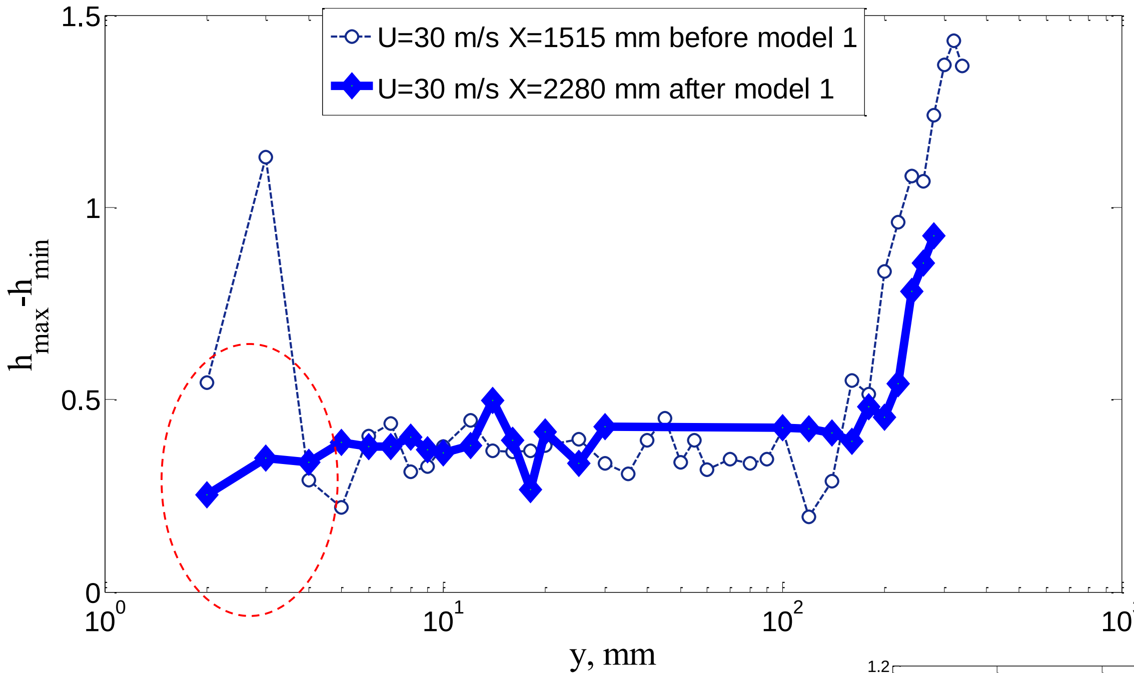
PDF

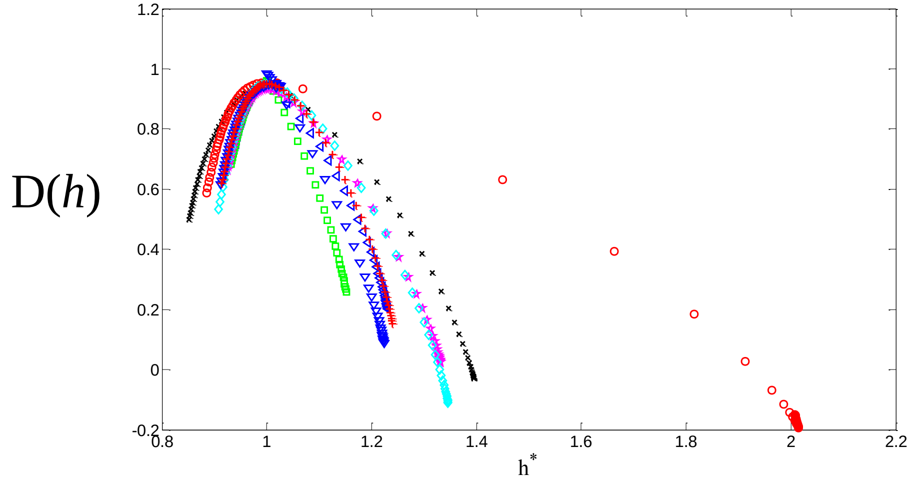


U=20 м/с
Y=14 мм
X=1515 мм



D(h) in TBL

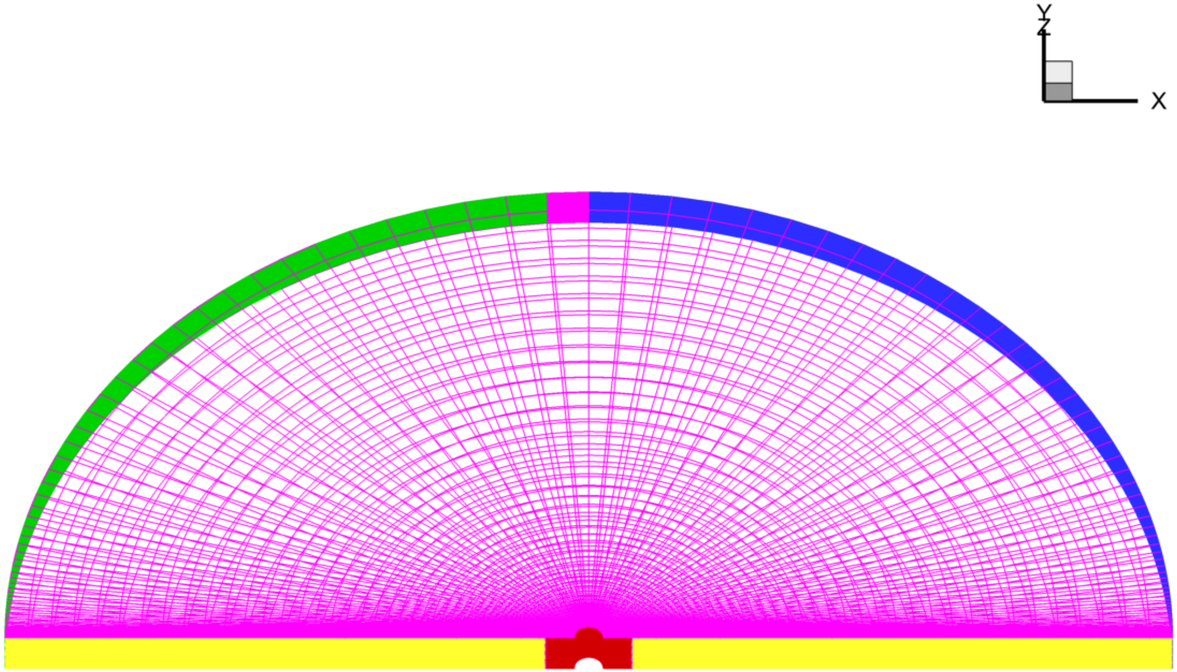




$\delta_l \upsilon \sim (l/L)^h$

With probability $P_h(l) \sim l^{3-D(h)}$

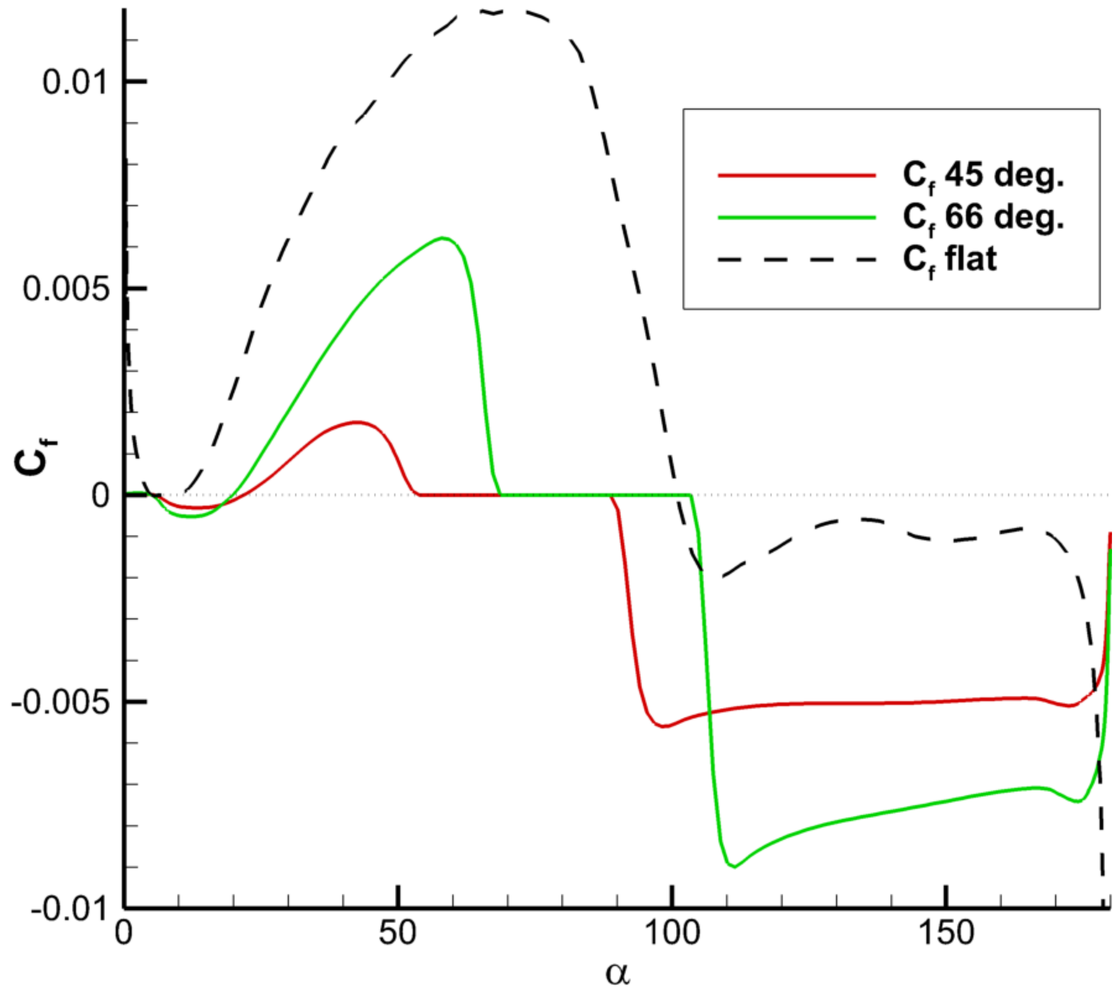
Численный эксперимент:
задача об обтекании половины цилиндра



Сетка в трёх измерениях и граничные условия

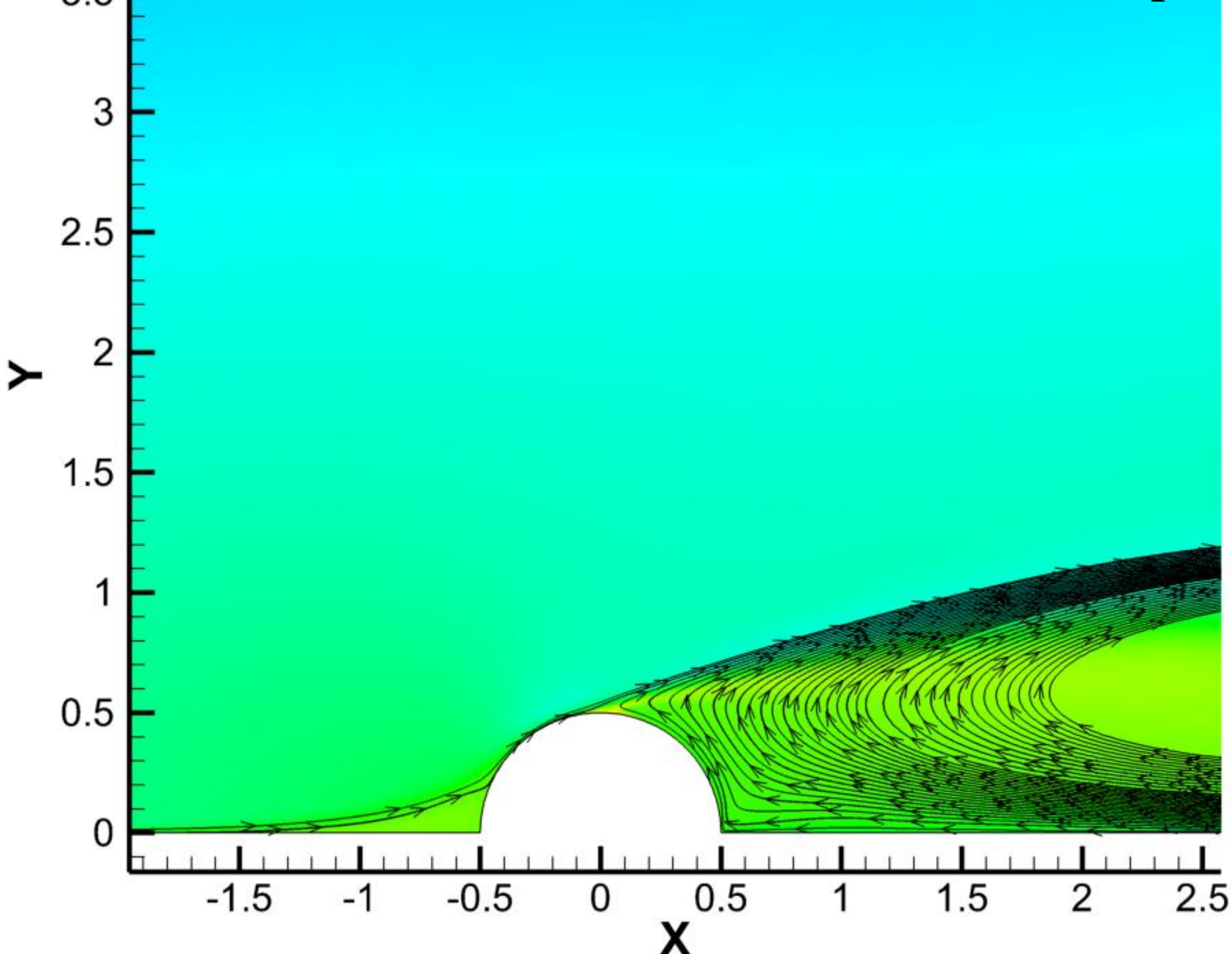
Задаваемые в расчетах граничные условия : Зелёному цвету соответствует граничное условие типа "поток на бесконечности", синему - "выход" (экстраполяция нулевого порядка), жёлтому - "плоскость симметрии/стенка с проскальзыванием", а красному - "стенка с прилипанием". При расчетах с шероховатой вставкой ей соответствует область от I=76 до I=103 включительно и от 87 до 114 ячейки . Таким образом, начало шероховатой вставки располагается на 45° или на 66°, ширина её составляет 45°. Настраиваемыми в программе параметрами, определяющими газодинамические величины в набегающем потоке являются число Маха и Re.

Численный эксперимент:
задача об обтекании половины цилиндра



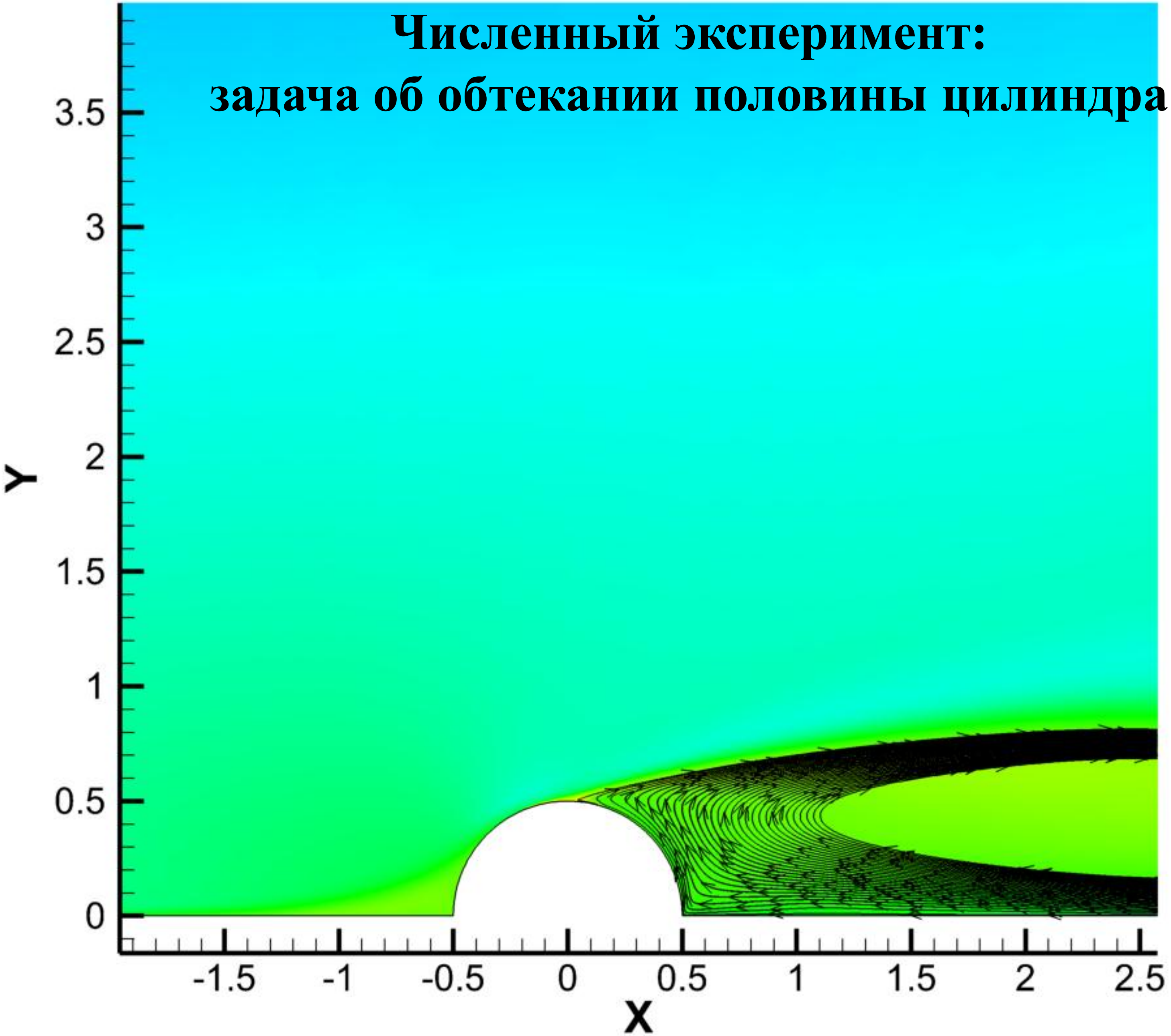
Коэффициент трения C_f от угловой переменной цилиндра .
Ширина фрактальной шероховатой вставки по углу 45°, середина - при положении вставки на 45° и 66°. M=0,2, Re=5x10^5, в зонах над вставкой C_f условно показан равным 0, пунктир – гладкий цилиндр.

Численный эксперимент:
задача об обтекании половины цилиндра



Распределение температуры и линии тока; начало вставки на 45°.
Точка отрыва на 84.5°.

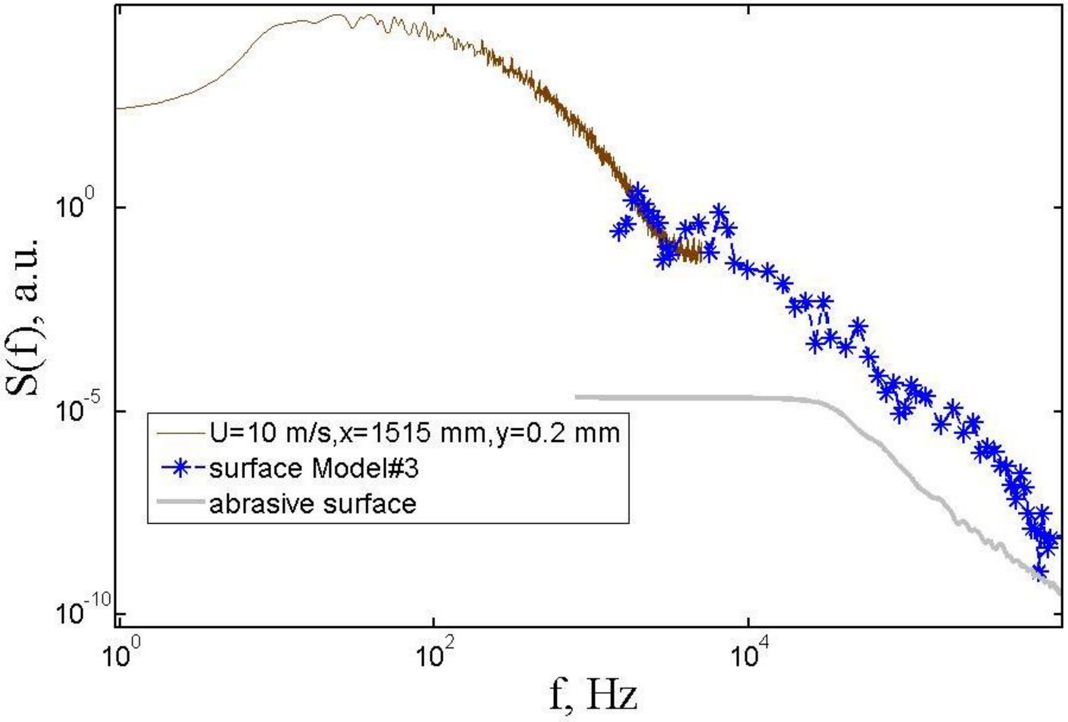
Численный эксперимент: задача об обтекании половины цилиндра

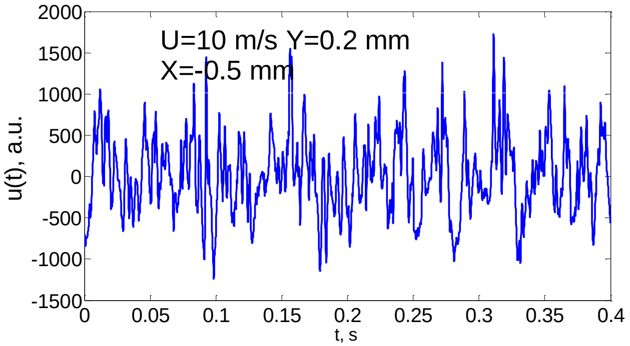


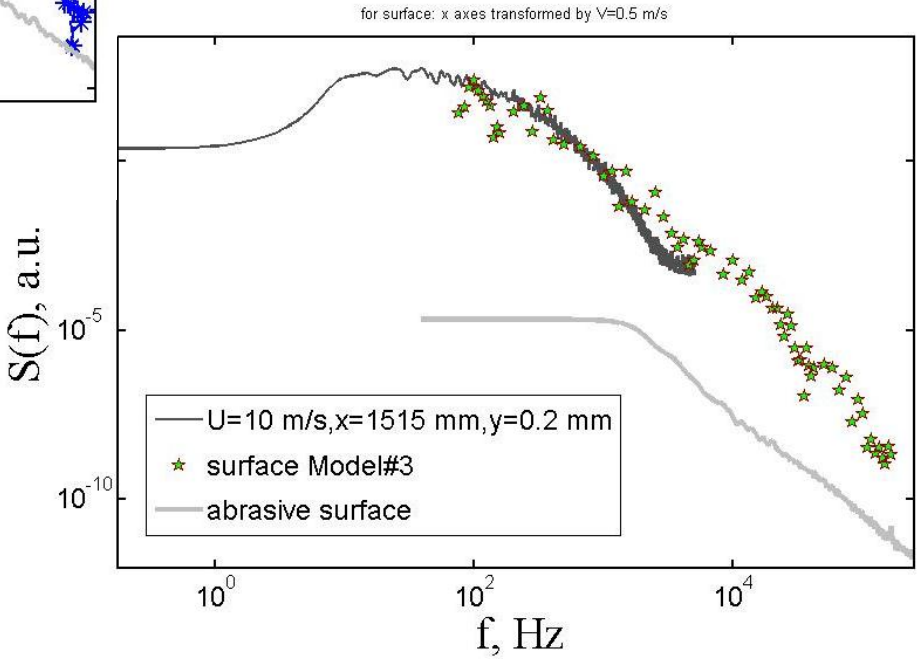
Распределение температуры и линии тока; начало вставки на 66°.

Точка отрыва на 90.7°.

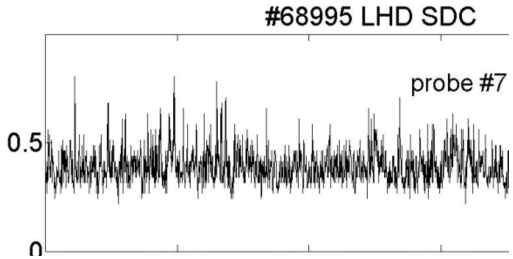
Spectrum in TBL and surface relief are identical







non-Gaussian statistics of edge turbulence : can deposit porous cauliflower-type surface



Budaev e a, Physica A, 2007

Levy –flights, H=0.7 superdiffusion

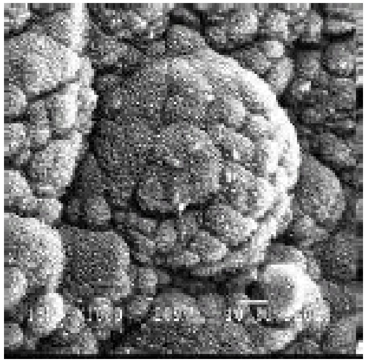
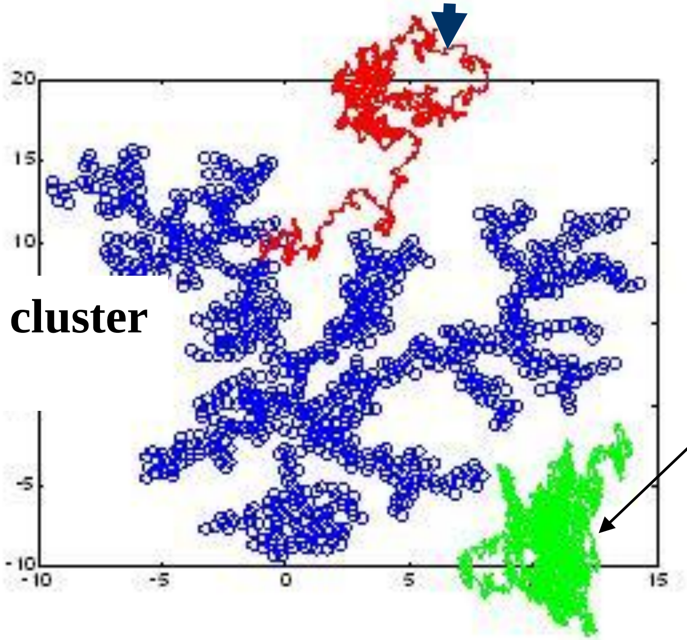


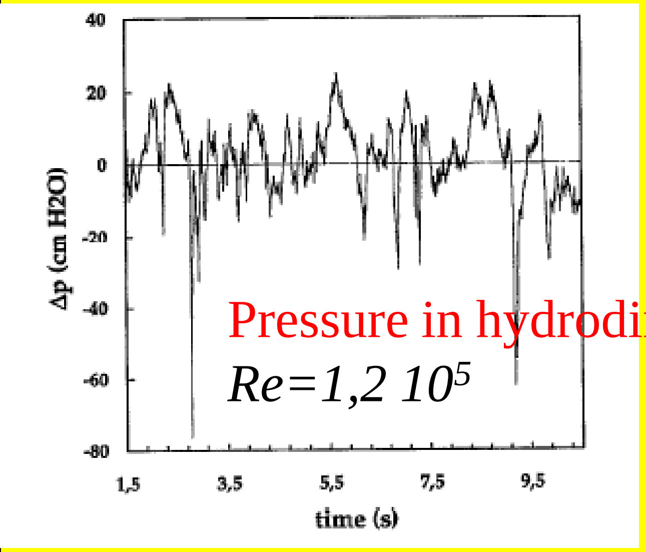
Fig.3. Globular film from ?-10 vacuum chamber × 1000.

Random walks, H=0.5 classic Brownian diffusion

fractal cluster

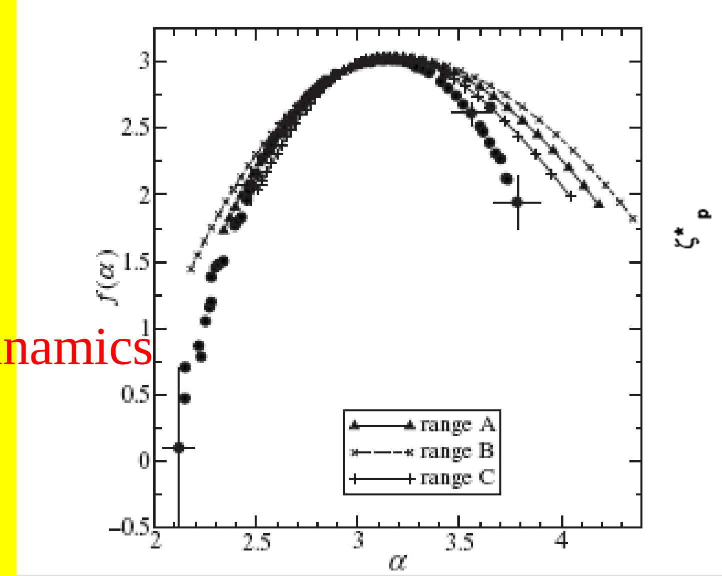


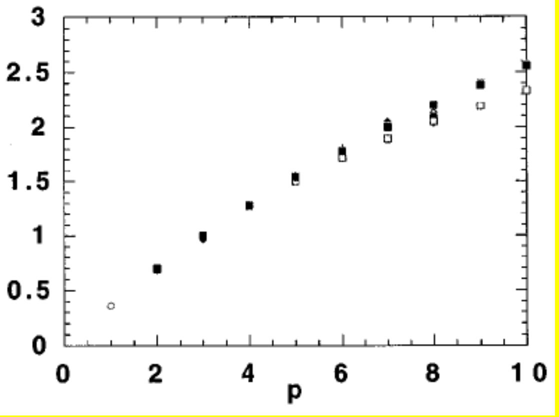
Comparison: neutral fluids and plasma



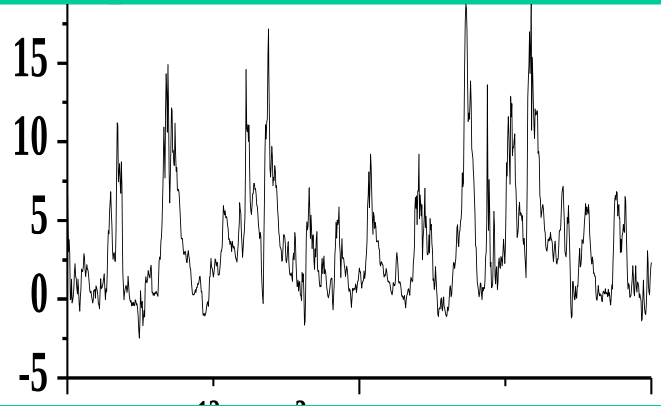
Pressure in hydrodinamics

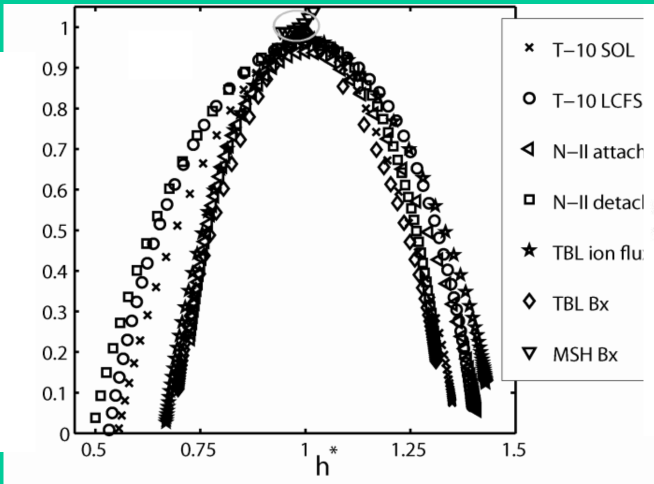
Re=1,2 10^{5}

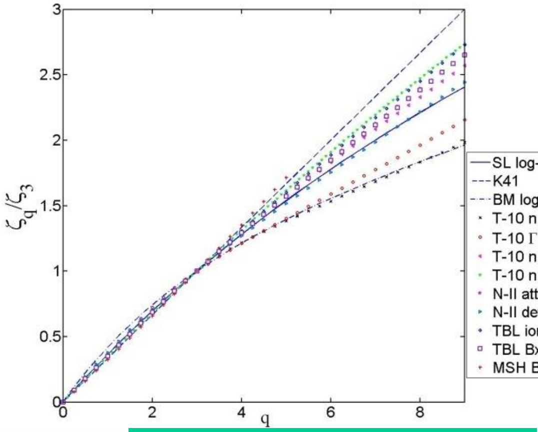


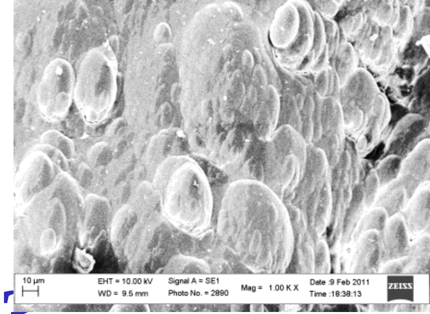


Plasma edge in tokamak









Aggregation–Fragmentation Processes and Wave Kinetics:

formal correspondence between the isotropic 3-wave kinetic equation and the rate equations for a non-linear fragmentation–aggregation process

There is a conceptual analogy between energy transfer between scales in turbulence and mass transfer between clusters in aggregation. Concepts and techniques from turbulence have proven useful in analysing certain aspects of aggregation problems.

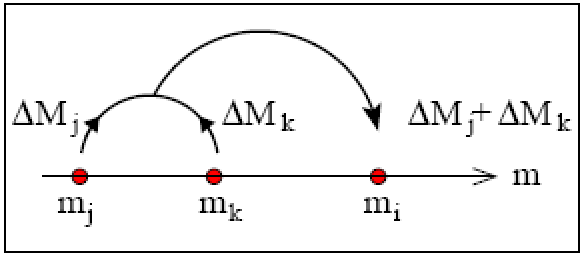
C. Connaughton, R. Rajesh, and O. Zaboronski, PRL (2005)

When sources and sinks of energy, widely separated in frequency, are added to the wave kinetic equation, it can be shown to have exact stationary solutions corresponding to a cascade of energy through frequency space from the source to the
sink. The cascade solution is known as the Kolmogorov-Zakharov (K-Z) spectrum; it describes an intrinsically non-equilibrium state of the wave field

The cluster size distribution of a statistically homogeneous system evolves according to the Smoluchowski coagulation equation:

$m_1 + m_2 \rightarrow m$

$$\frac{\partial N_m(t)}{\partial t} = \int_0^\infty dm_1 dm_2 K(m_1, m_2) N_{m_1} N_{m_2} \delta(m - m_1 - m_2) - 2\int_0^\infty dm_1 dm_2 K(m, m_1) N_m N_{m_1} \delta(m_2 - m - m_1) + J\,\delta(m - m_0)$$



- Collision kernel, Mean Field Approximation :

$$K(hm_1, hm_2, hm) = h^\zeta K(m_1, m_2, m)$$

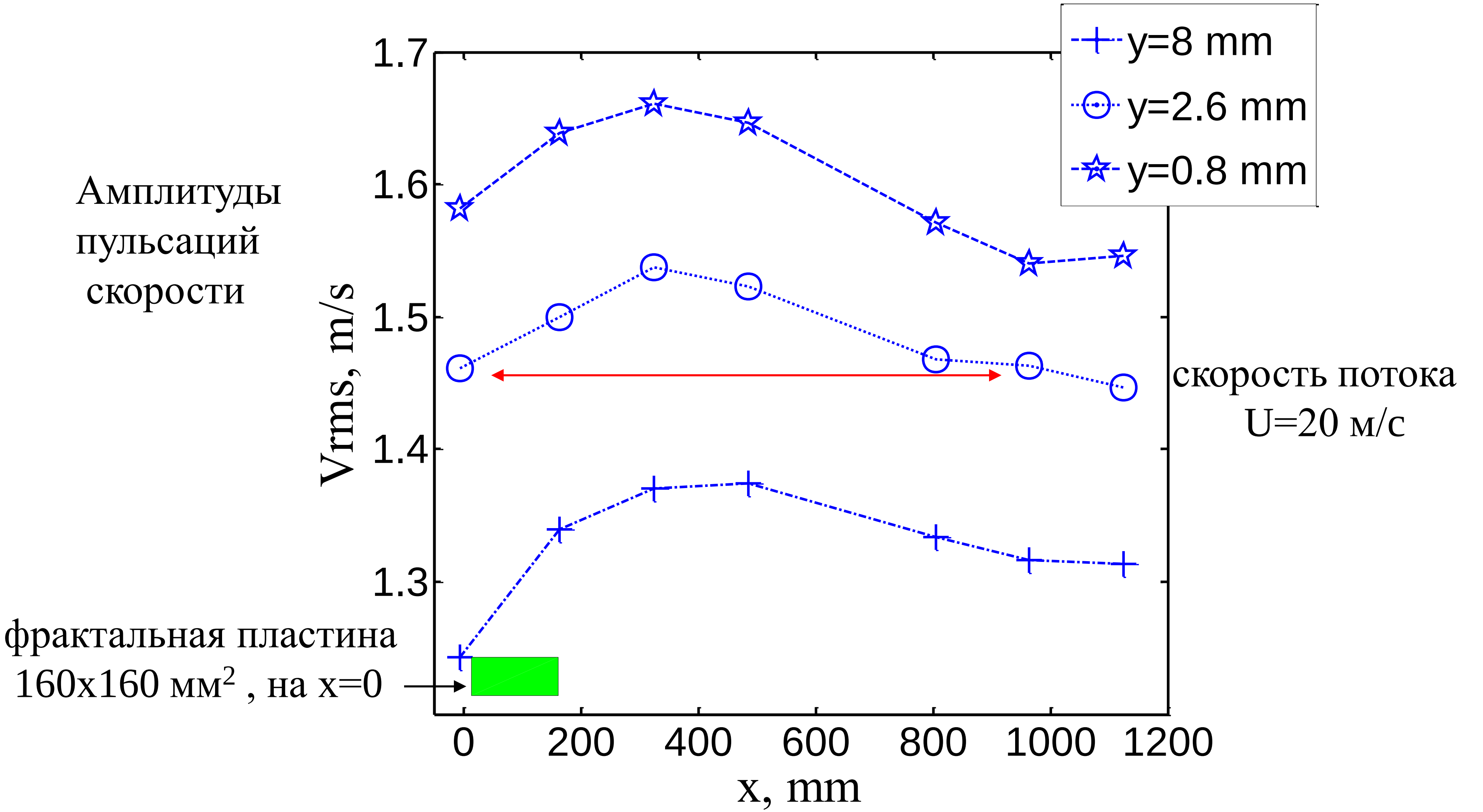
$$K(m_1, m_2, m) \sim m_1^\mu m_2^\nu$$

- Self-similar solutions:

$$\mu + \nu = \zeta.$$

Kolmogorov-Zakharov spectrum $N(m) = C\, m^{-x_K}$ $\quad x_K = \frac{3+\zeta}{2}$

Эксперимент в АДТ Т-36И [1]

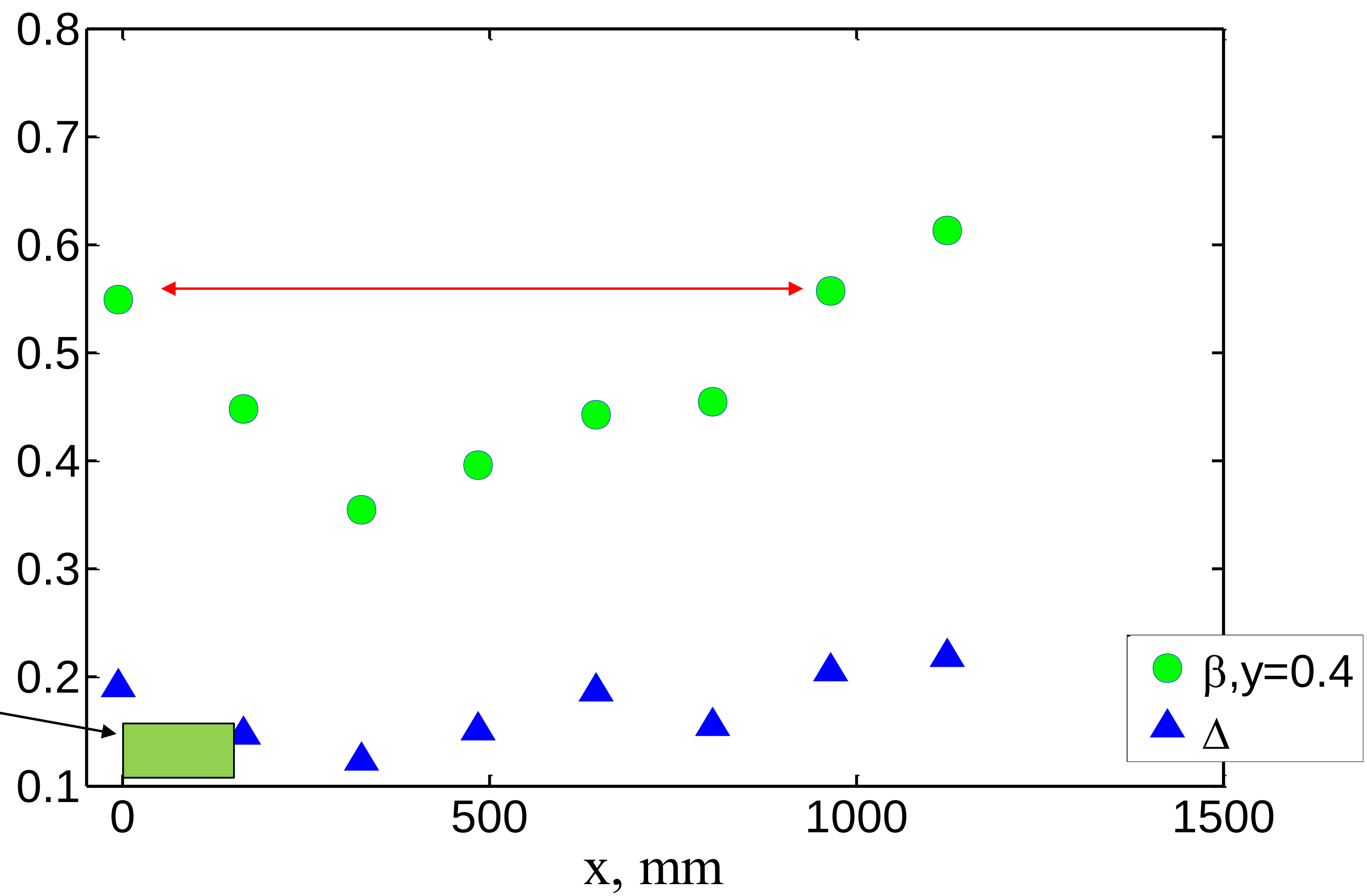


Значительное влияние на характеристики ТПС вниз по потоку на масштабах более 5-6 размеров пластины

Эксперимент в АДТ Т-36И [1]

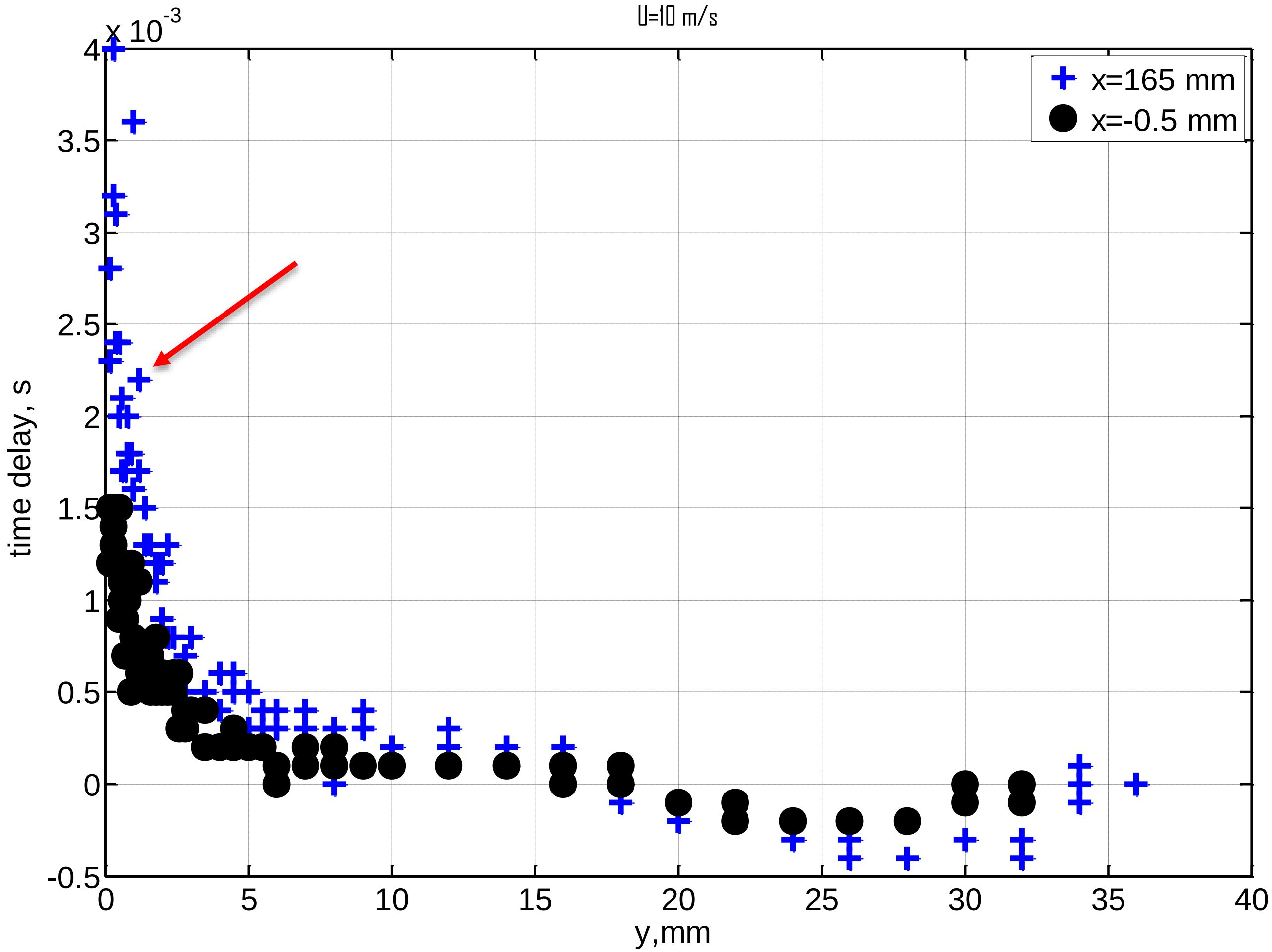
Статистические свойства ТПС - параметры логпуассоновского скейлинга β и Δ [1] вдоль потока после фрактальной пластины; y=0.4 мм z=-19 мм, U=20 м/с.

фрактальная пластина 160x160 мм^2 установлена при x=0



Значительное влияние на характеристики ТПС вниз по потоку на масштабах более 5-6 размеров пластины

Эксперимент в АДТ Т-36И [1]

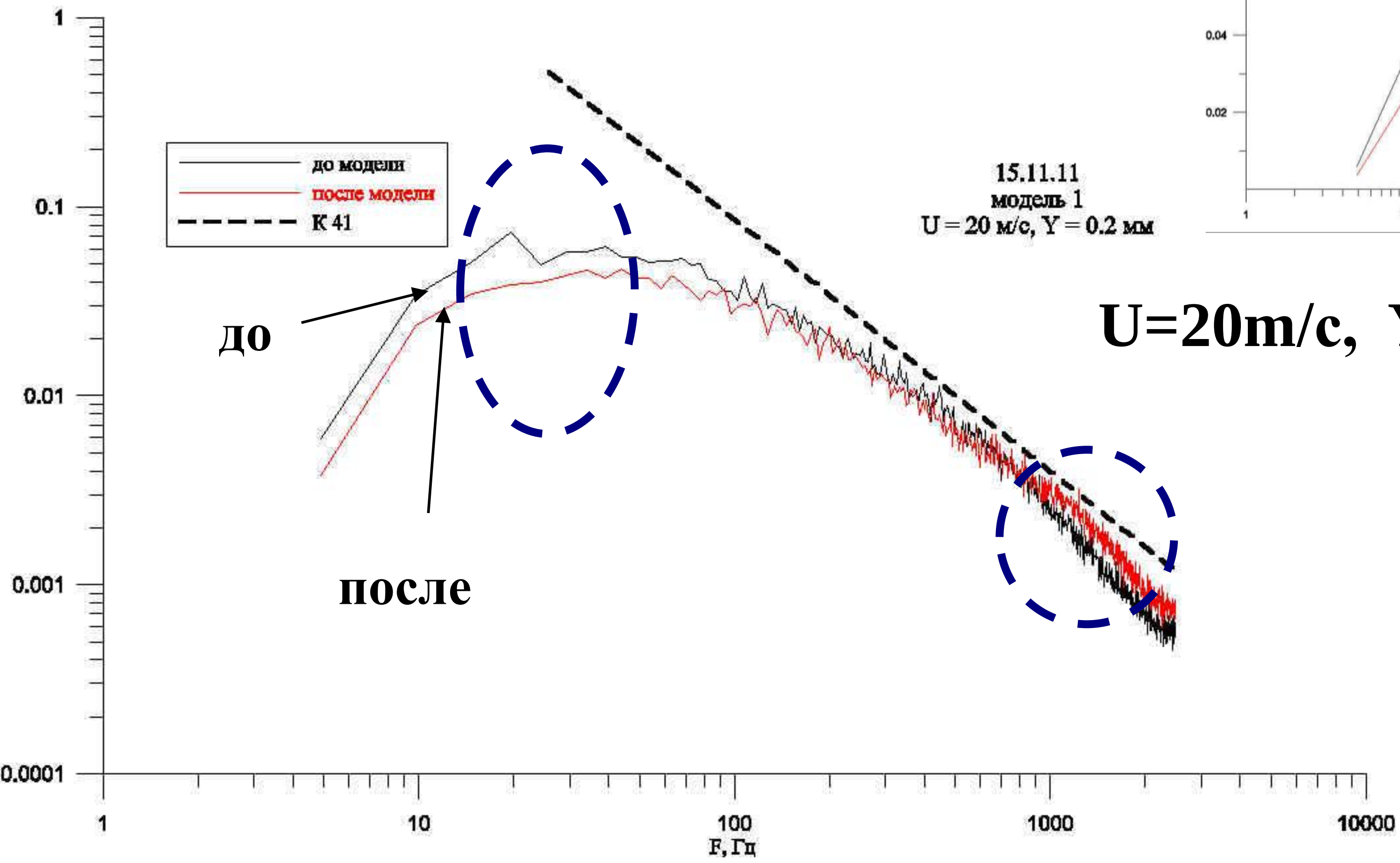


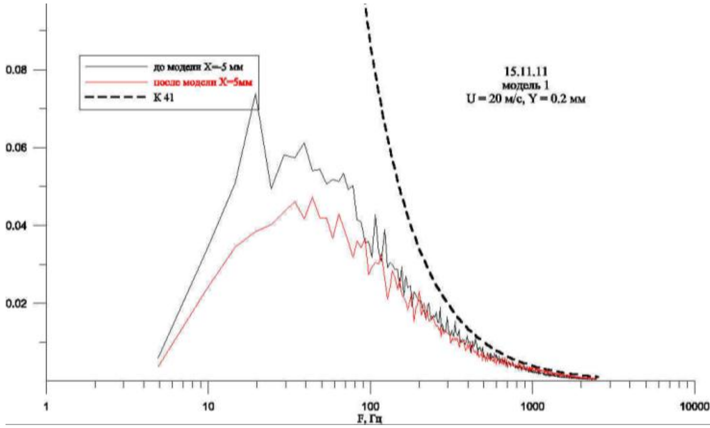
фрактальная пластина 160х160 мм^2 установлена при х=0

Кросскорреляционное время между пульсациями скорости разделенными 2 мм по высоте в зависимости от высоты у ТПС: 5 мм до (о) и 5 мм после (+) фрактальной пластины , U=10 м/с

Наблюдается увеличение времени поперечных корреляций

Spectrum change in TBL

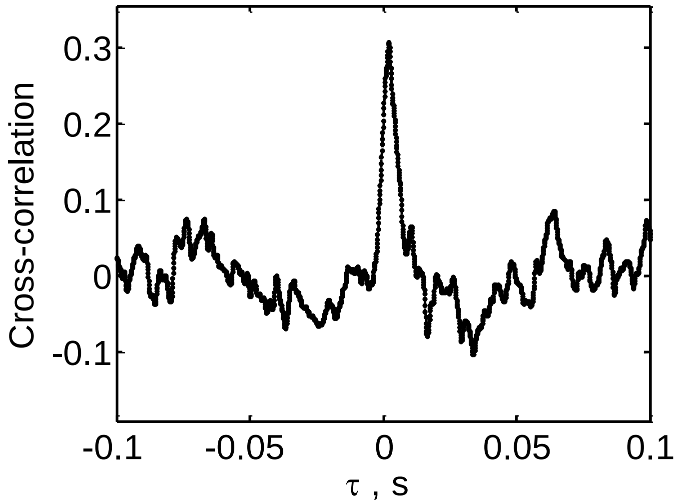




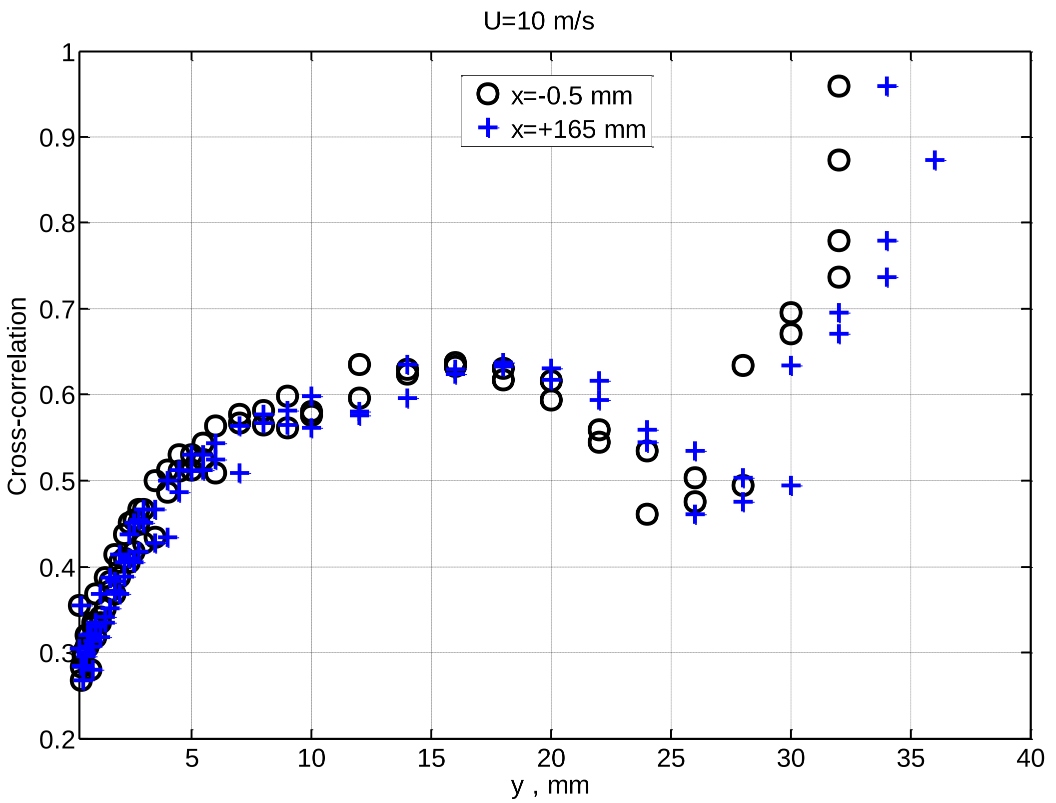
U=20m/c, Y= 0,2 mm

Low-frequency range suppressed , high-frequency range growth : coherent eddies destroyed

Кросс-корреляции над плоской моделью
Эксперимент в АДТ Т-36И [1]



Кросс-корреляции между пульсациями скорости при y=0,2 мм и при y=2,2мм, x=805 мм . Скорость потока U= 10 м/с.



Коэффициент кросс-корреляции в зависимости от высоты y