COMPASS
INSTITUTE OF PLASMA PHYSICS ASCR

gymnázium
jana nerudy

Jaderná fúze v tokamacích a využití COMSOL Multiphysics v ÚFP AV ČR

Václav Sedmidubský
Scientific supervisor: Mgr. Jan Horáček, dr. és sc

- Jaderná fúze v tokamacích
- Fast divertor sweeping study (rozmítání plazmatu)
- => využití COMSOL Multiphysics

Zdroje energie

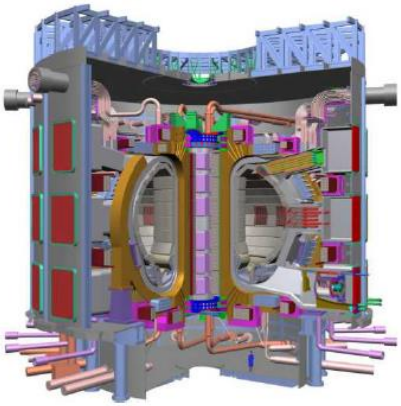
Fosilní paliva

Větrné

Vodní přehrady

Geotermální

Termojaderná fúze



Biomasa (dřevo)

Jaderné štěpení

Solarní

Zdroje energie

Fosilní paliva

Klimatické změny
Omezené zásoby

Geotermální

Nedostatečné
lokální

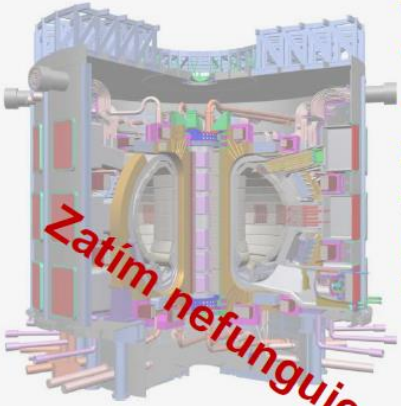
Jaderné štěpení

Radioaktivní odpad
Jaderné havárie
Iracionálně-vyhrocený
odpor veřejnosti

Větrné

Nedostatečné
přerušované

Termojaderná fúze



Zatím nefunguje

Wagner:
Více než
~20% nelze
z větru a
solárů
pokrýt kvůli
nestálosti

Vodní přehrady

nedostatečné

Biomasa (dřevo)

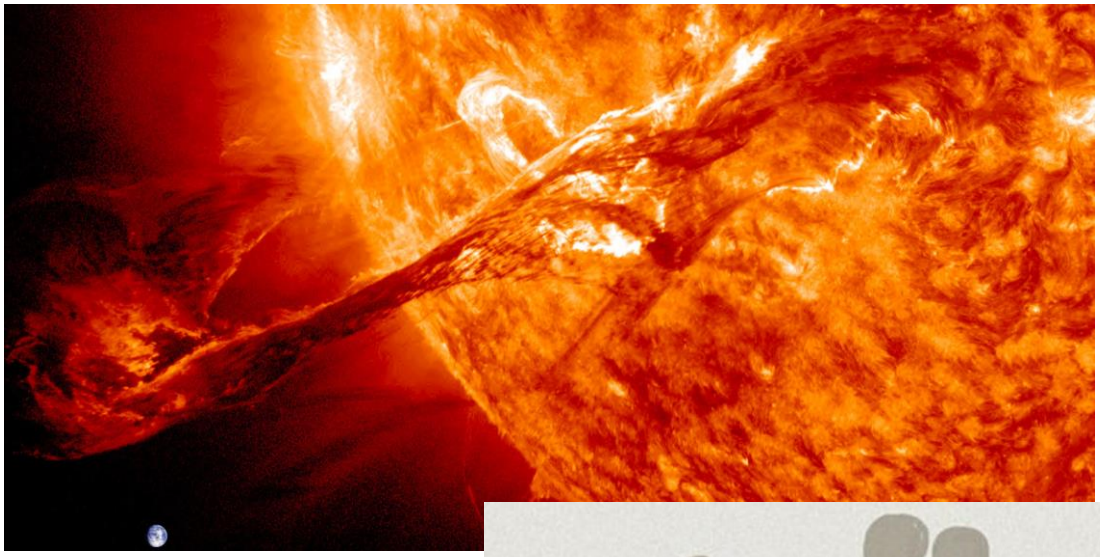
Pouze na topení

Solární

Nedostatečné
Přerušované
drahé

Jaderná fúze

- energie Slunce
- slučování lehkých atomových jader
- plasma = ionizovaný plyn
- Deuterium + Tritium => He + neutron + E
  - nejlehčí v pozemských podmínkách
  - plasma 150 mil. °C, 1 atm
- Odpadní látky reakce: Helium, neutrony
  - **NEŠKODNÉ**
- Neutronový tok - radioaktivní komponenty
  - **za 100 let** recyklovatelné
- **4 000 000 krát efektivnější** než spalování uhlí
  - **30 gramů H a Li** na **celoživotní** energetickou spotřebu Evropana



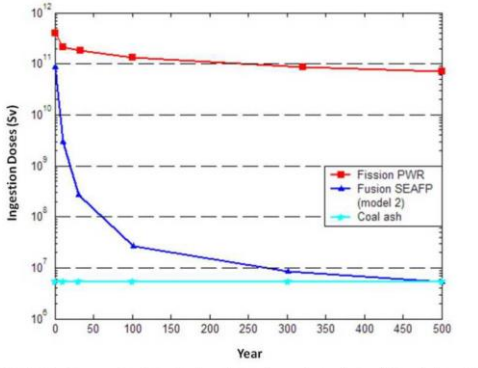
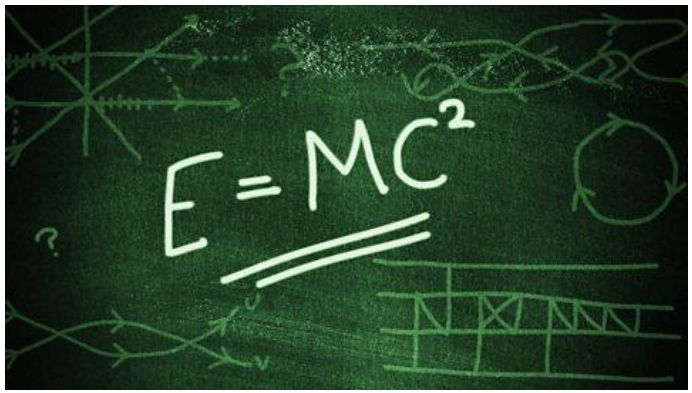
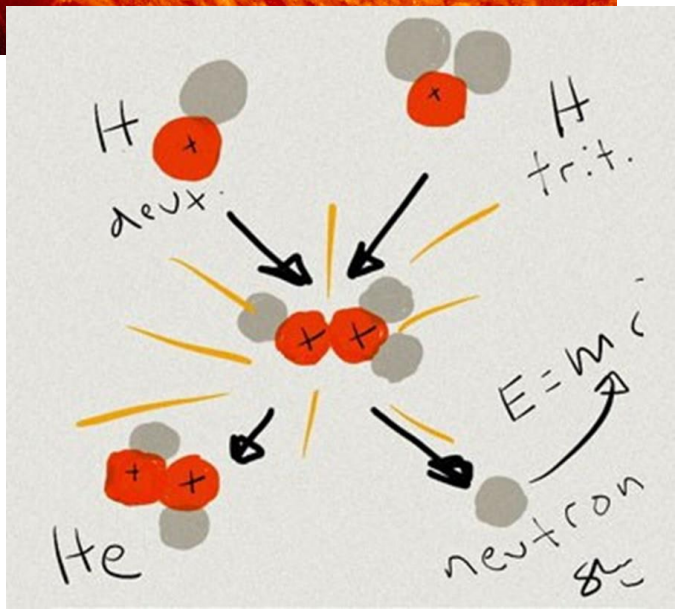
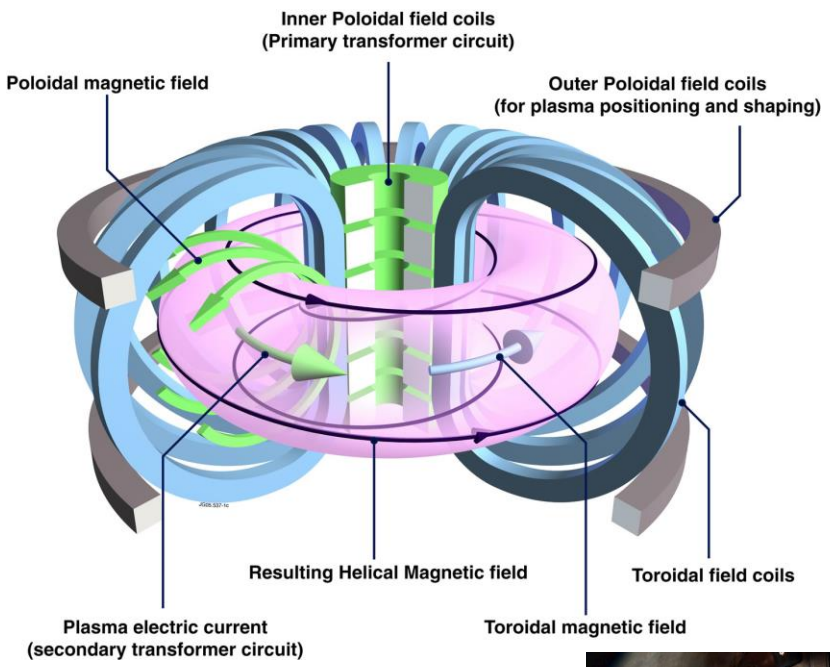


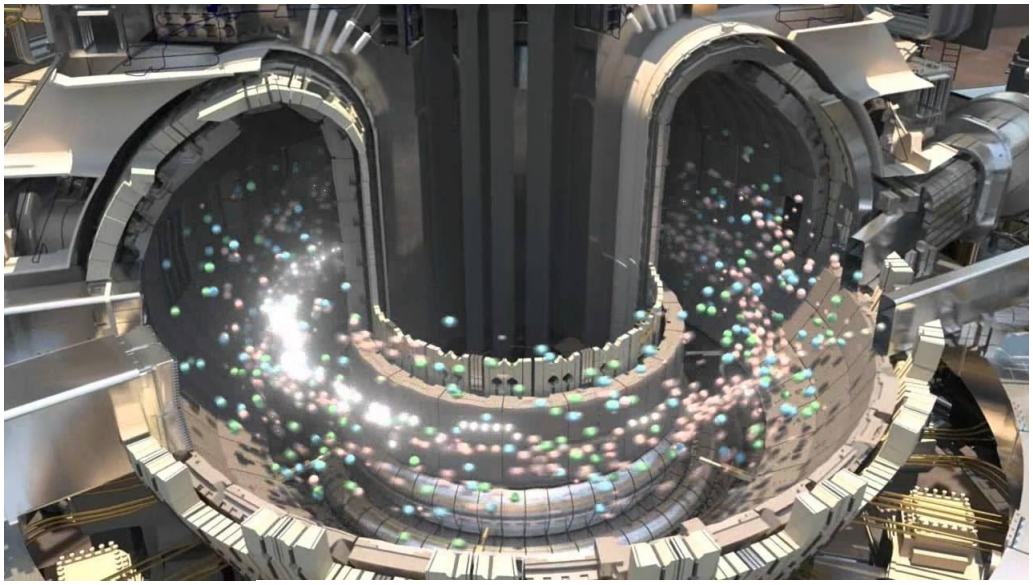
FIG. 1.19. Development of radiotoxicity for a fusion plant, a fission plant and the ash of a coal plant. It is assumed that all the plants produce the same quantity of electricity. The volume of coal ash is of course 2–3 orders higher [1.71].



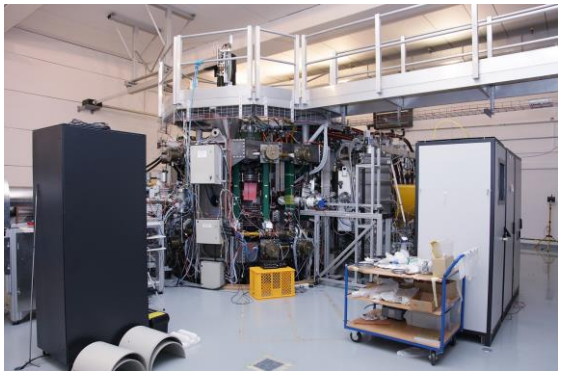


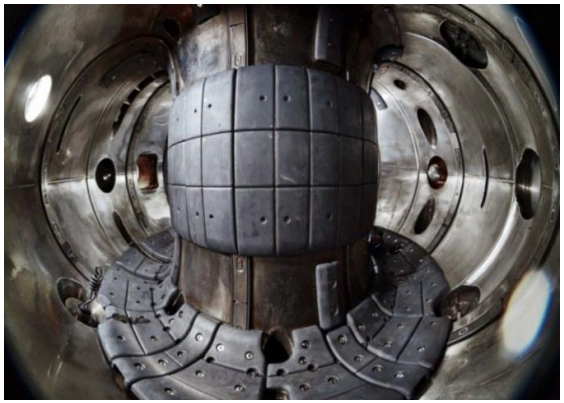
Tokamak

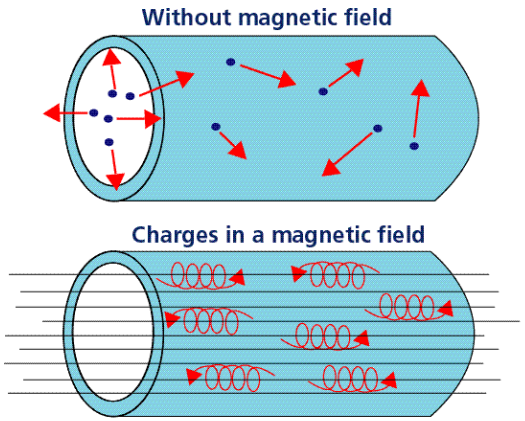




Charges in a Magnetic Field

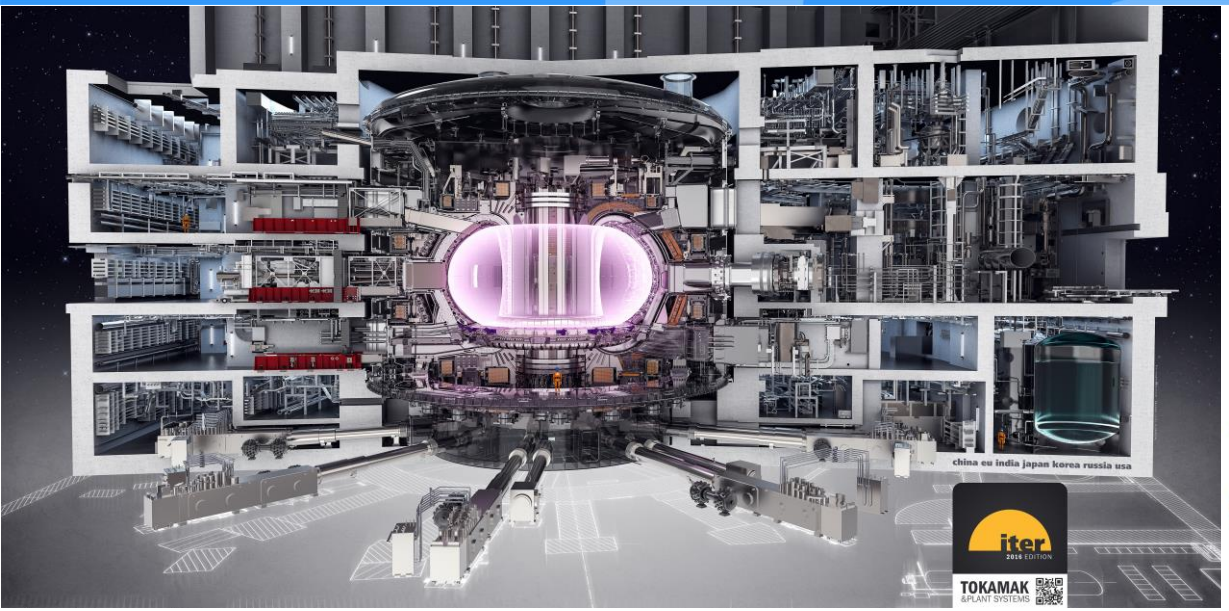


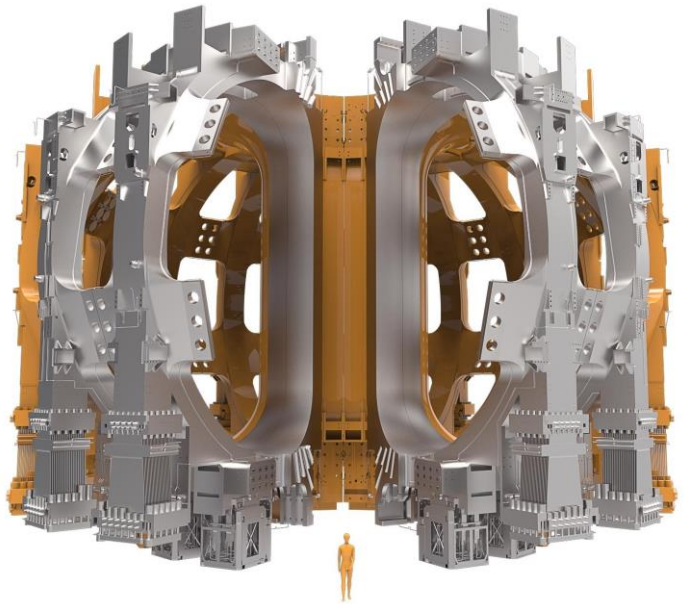


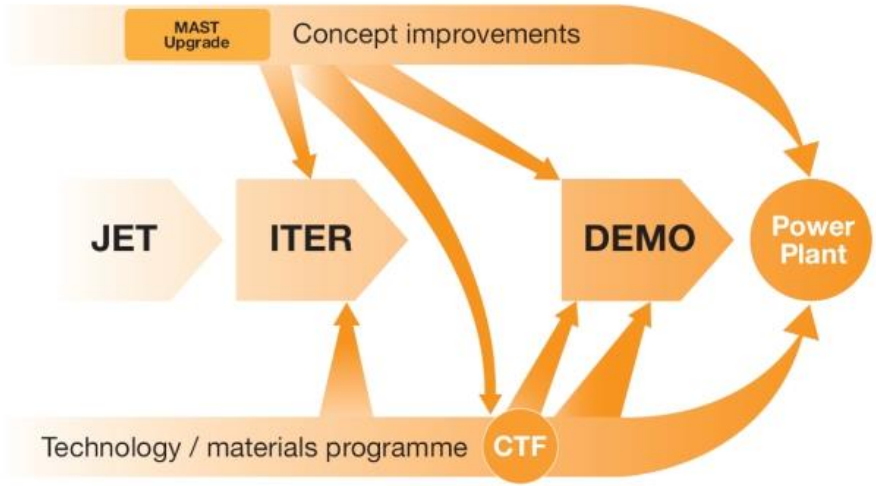


UKAEA Fusion

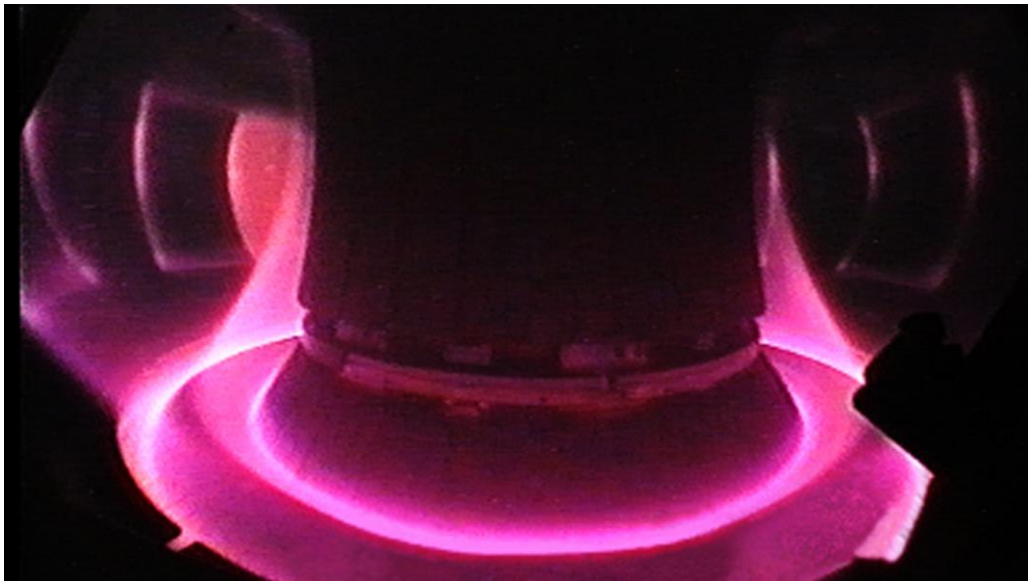
ITER a DEMO

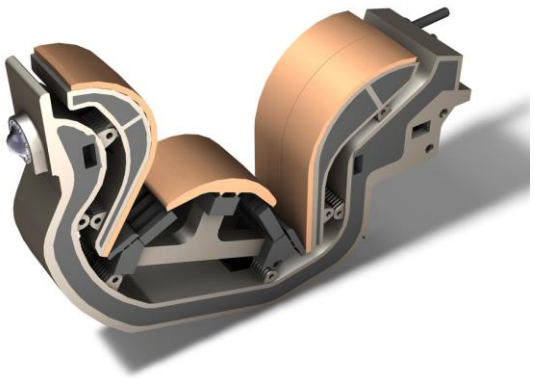

china eu india japan korea russia usa
iter
2016 EDITION
TOKAMAK
&PLANT SYSTEMS

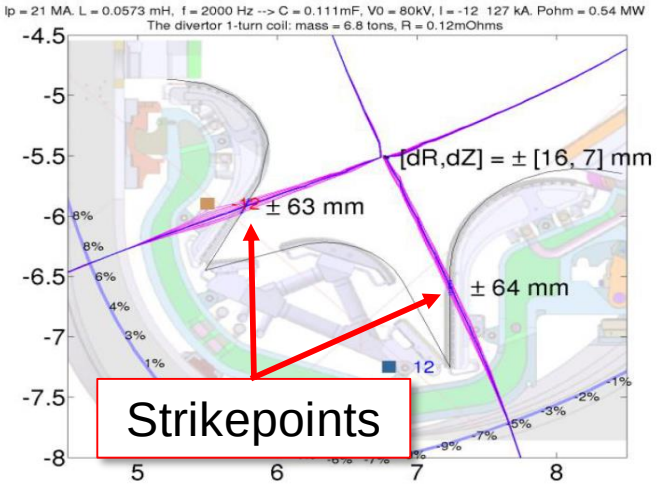


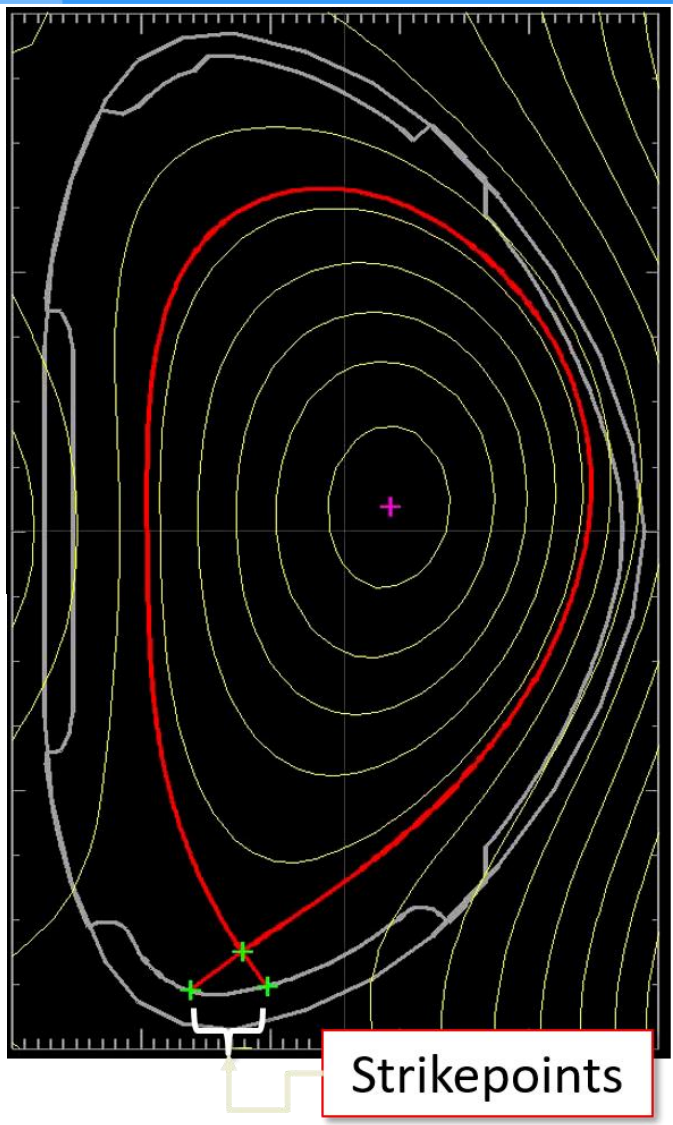

MAST
Upgrade
Concept improvements
JET
ITER
DEMO
Power
Plant
Technology / materials programme
CTF

Divertor a tepelný tok





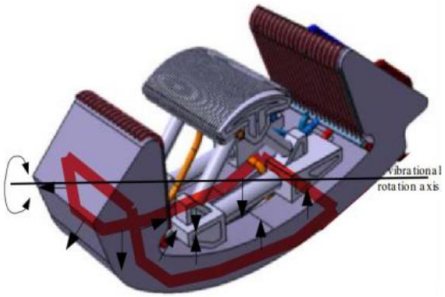


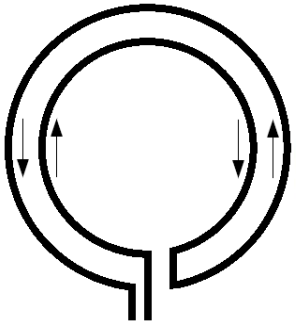


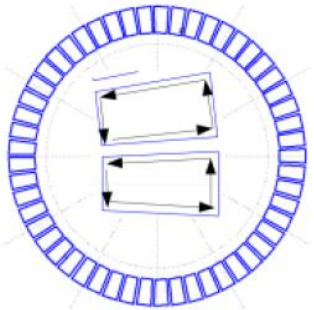
Rozmítání tepelného toku

- tepelný tok nutno zmenšit **20 - 80 krát (f_{sup})**
- **metoda rychlého rozmítání strike-pointu**
  - oscilační magnetická perturbace
- => zvětšení plochy dopadu plazmatu
- $f_{sup} = 1 + \sqrt{f_{sweep} * T_{ELM} * \frac{A_{shift}}{\lambda_q}}$
- **f_{sup} = 9**: 7,5 kHz, A_{shift} = 20cm

1. Toroidálně symetrická cívka

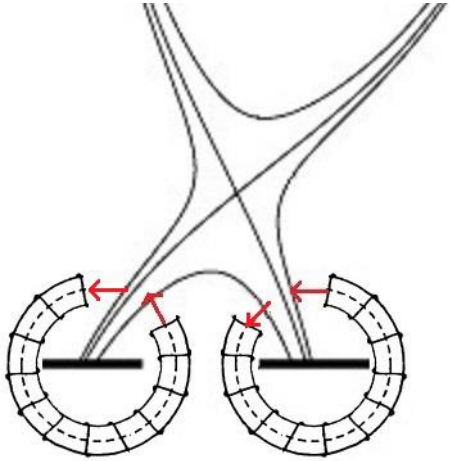


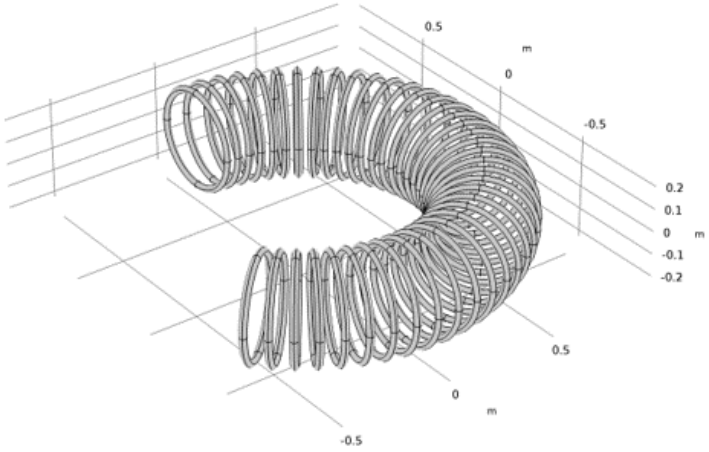


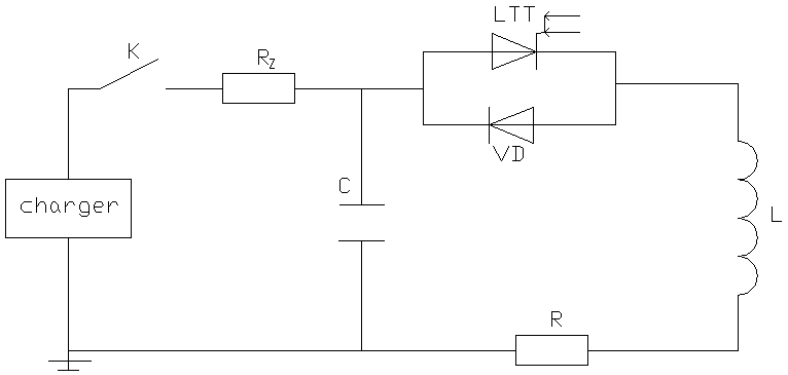


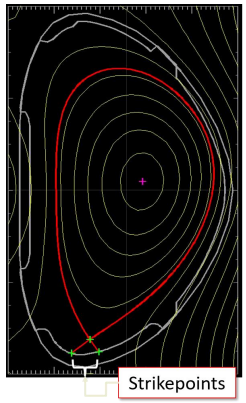
2. C-cívka

(R0 = 70cm, R = 21cm, N = 40 turns)





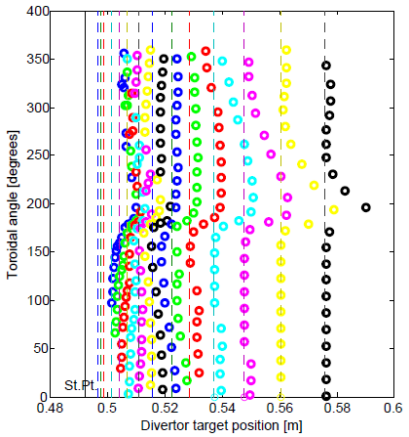


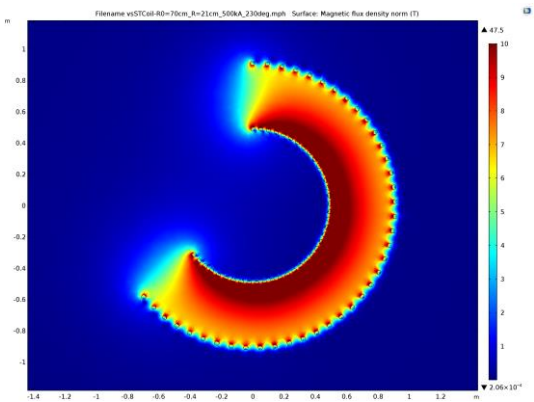


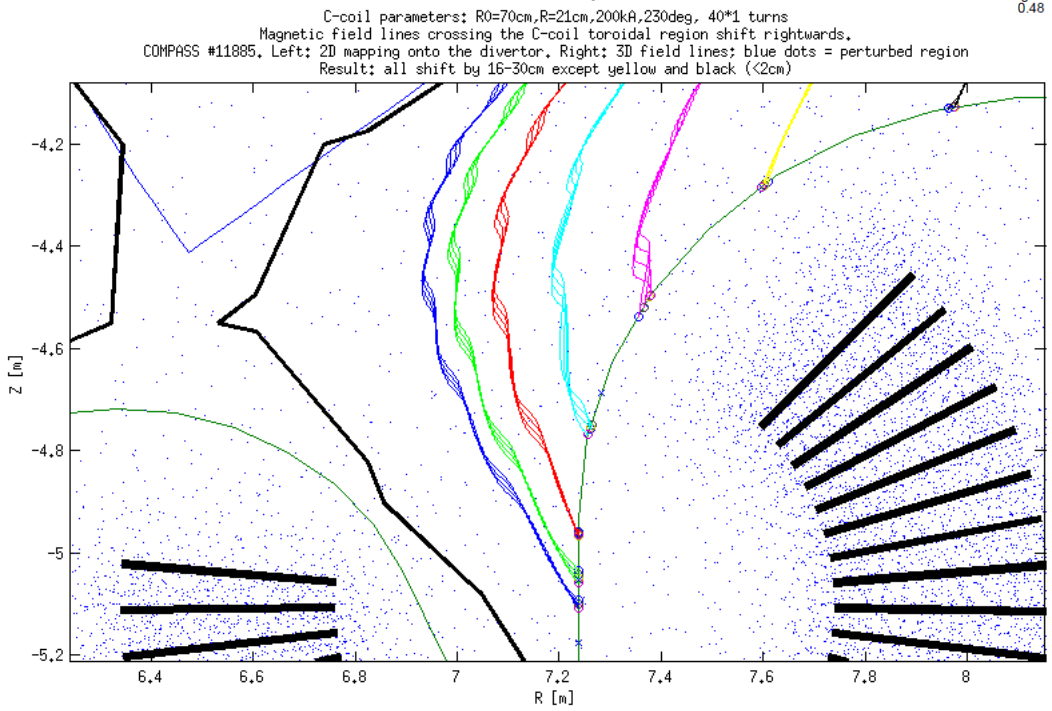
Magnetické pole a trackování siločar

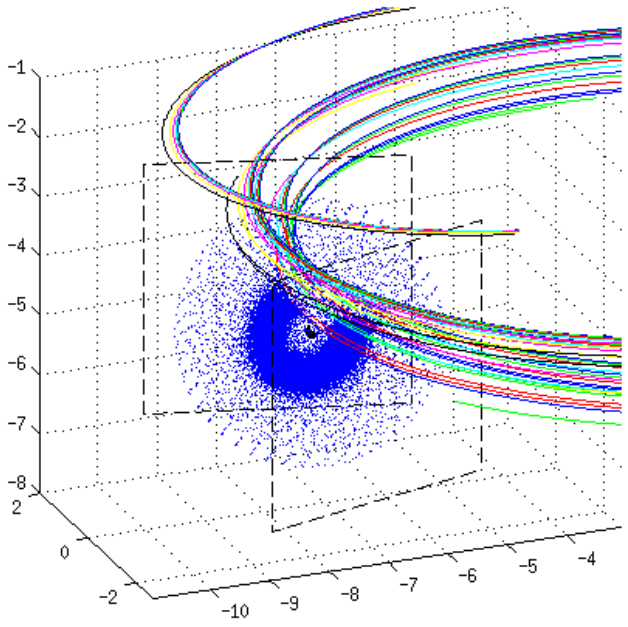
- COMSOL vytvoření magnetického pole C-cívky
- účinek magnetické perturbace?
- MATLAB trackování siločar
  - magnet. pole tokamaku + C-cívky

- 6 C-cívek
  - N = 40 turns, R0 = 70cm, R = 21 cm, I = 200 kA, 230deg
  - **A_{shift} ~ 20cm, 7,5 kHz => f_{sup} = 9**



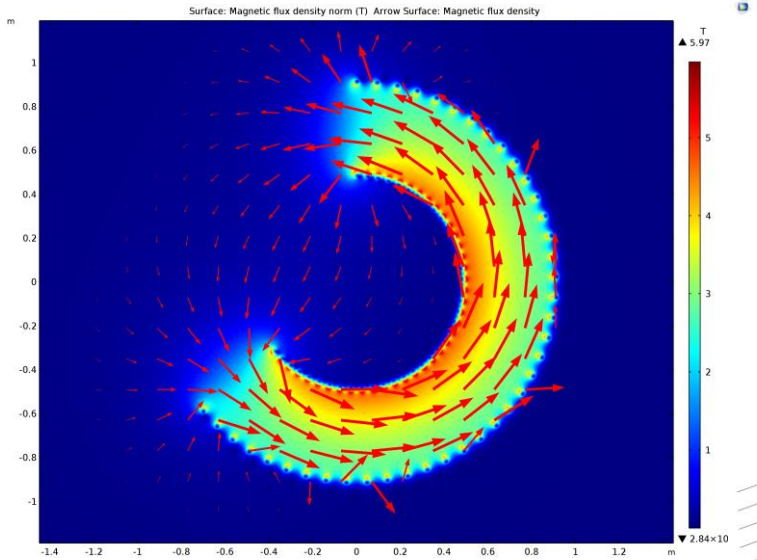




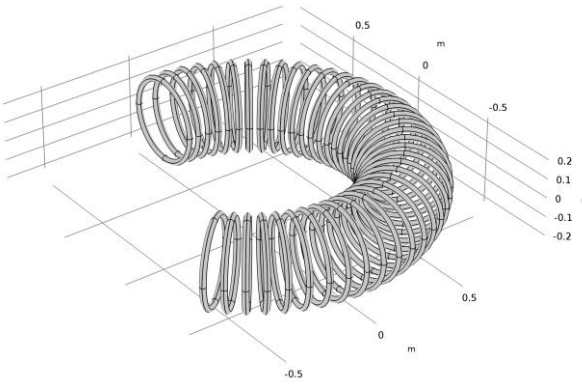


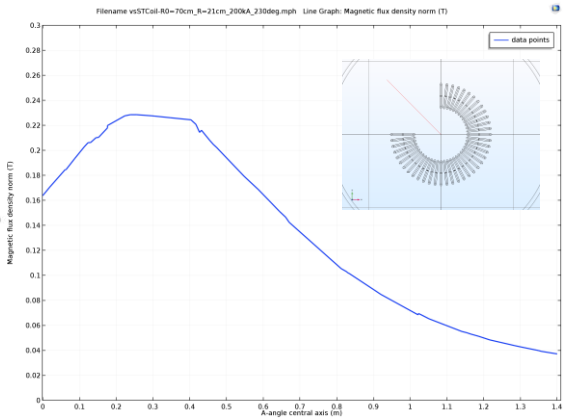
- Model magnetického pole C-cívky
  - Export do MATLABu
- Výpočet indukčnosti C-cívky

➢ $L = \frac{2 * W_m}{I^2}$ (W_m … *magnetic field energy*)



for DEMO	Toroidally symmetric coil	C-coil	
Počet cívek	54 cívek	2*54 cívek	2*6 cívek
N - počet závitů	1	7	40
U - napětí	18 kV	18 kV	914 kV
I = proud	400 kA	128 kA	200 kA
f_{sweep}	7,5 kHz	7,5 kA	7,5 kHz
Wm - ∑E mag. pole	4,3 MJ	2*1,3 MJ	2*11,5 MJ
L - indukčnost	1 μH	2,97 μH	97 μH
$f_{sup} = 9$	proveditelné	proveditelné	neproveditelné

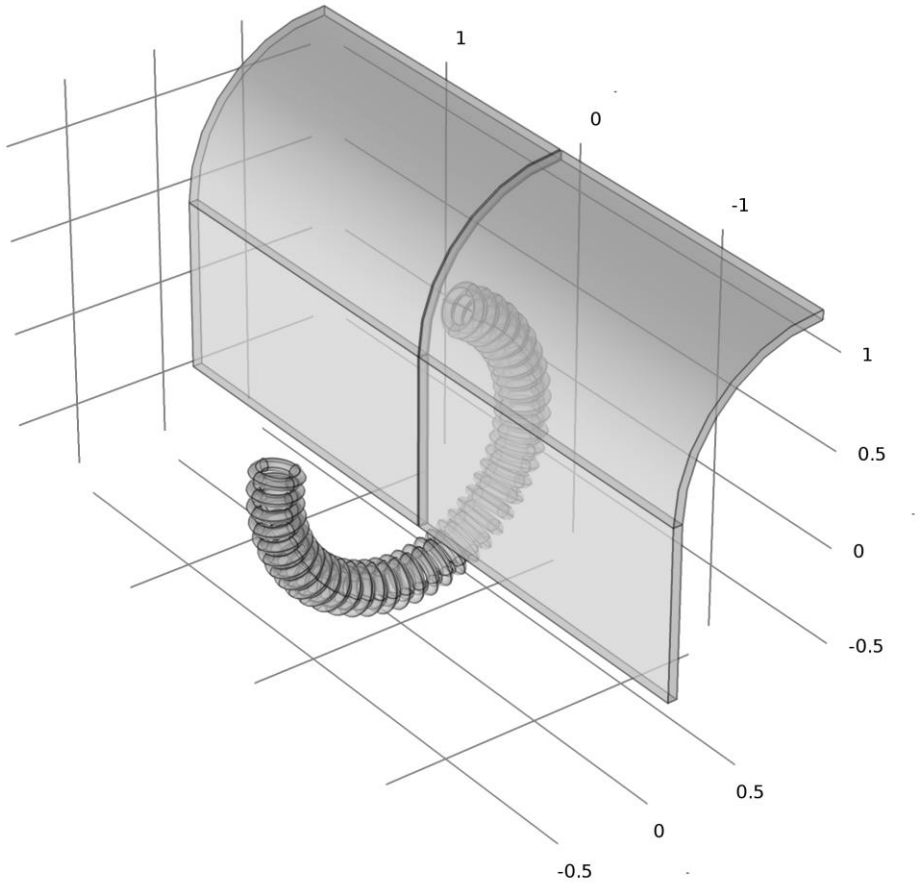




C-cívka s div. deskou

- C-cívka v komoře tokamaku DEMO
- Wolframová deska (divertor) „před cívkou“
- ➢ **foucaultovy vířivé proudy v desce**
- ➢ **=> vliv na výsledné magnet. pole**

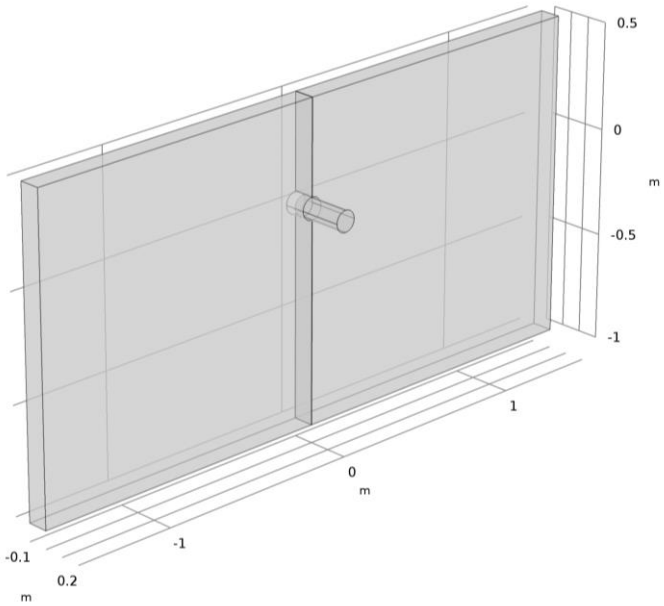
- aktuálně pracuji na modelu

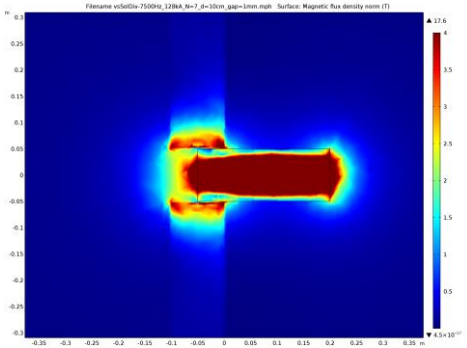


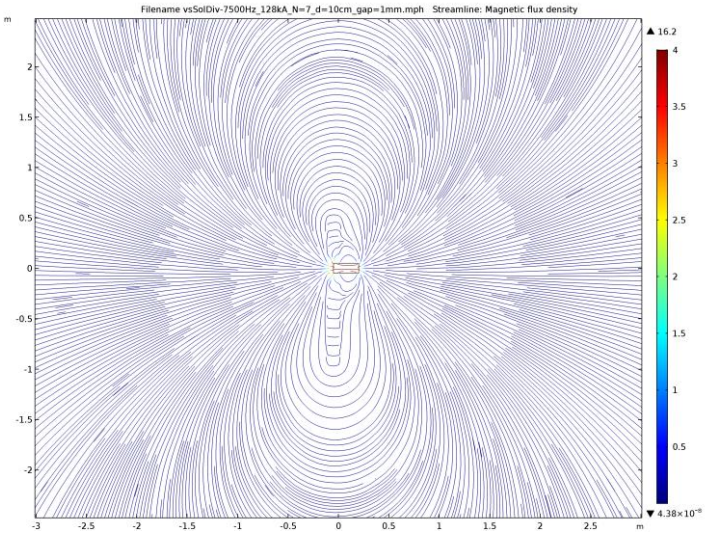
Solenoid

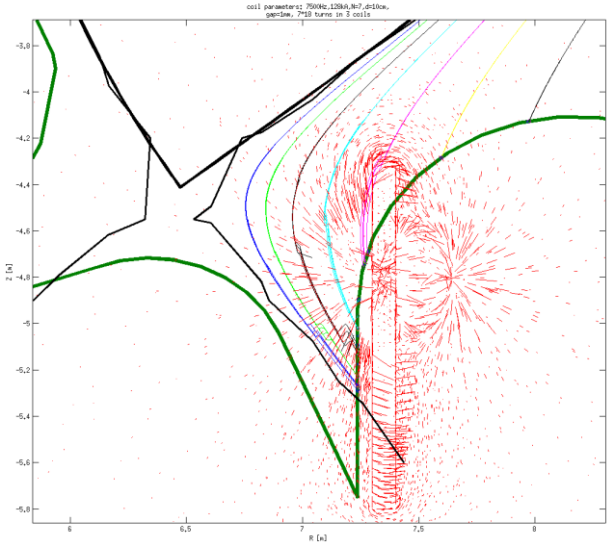
- rovná „nezahnutá“ cívka - **solenoid**
  - N = 7, l = 25 cm, d = 10 cm
  - I = 128 kA, f_{sweep} = 7,5 kHz
- **A_{shift} nedostatečný**
- **indukce foucaultových proudů v komoře**

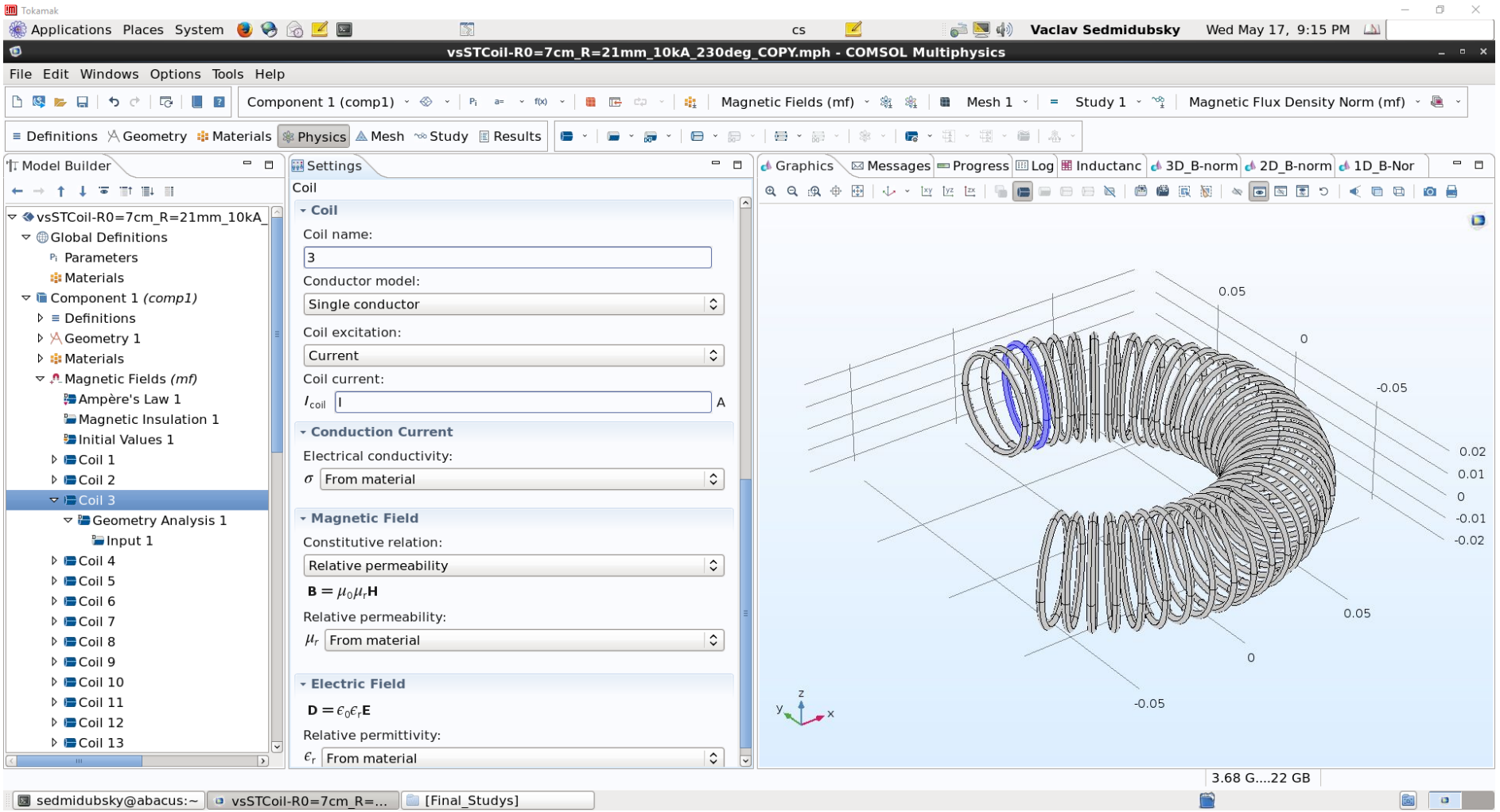
➢ **NEPROVEDITELNÉ**










Tokamak
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vsSTCoil-R0=7cm_R=21mm_10kA_230deg_COPY.mph - COMSOL Multiphysics
File Edit Windows Options Tools Help
Component 1 (comp1)
Magnetic Fields (mf)
Mesh 1
Study 1
Magnetic Flux Density Norm (mf)
Definitions Geometry Materials Physics Mesh Study Results
Model Builder
vsSTCoil-R0=7cm_R=21mm_10kA_
Global Definitions
Parameters
Materials
Component 1 (comp1)
Definitions
Geometry 1
Materials
Magnetic Fields (mf)
Ampère's Law 1
Magnetic Insulation 1
Initial Values 1
Coil 1
Coil 2
Coil 3
Geometry Analysis 1
Input 1
Coil 4
Coil 5
Coil 6
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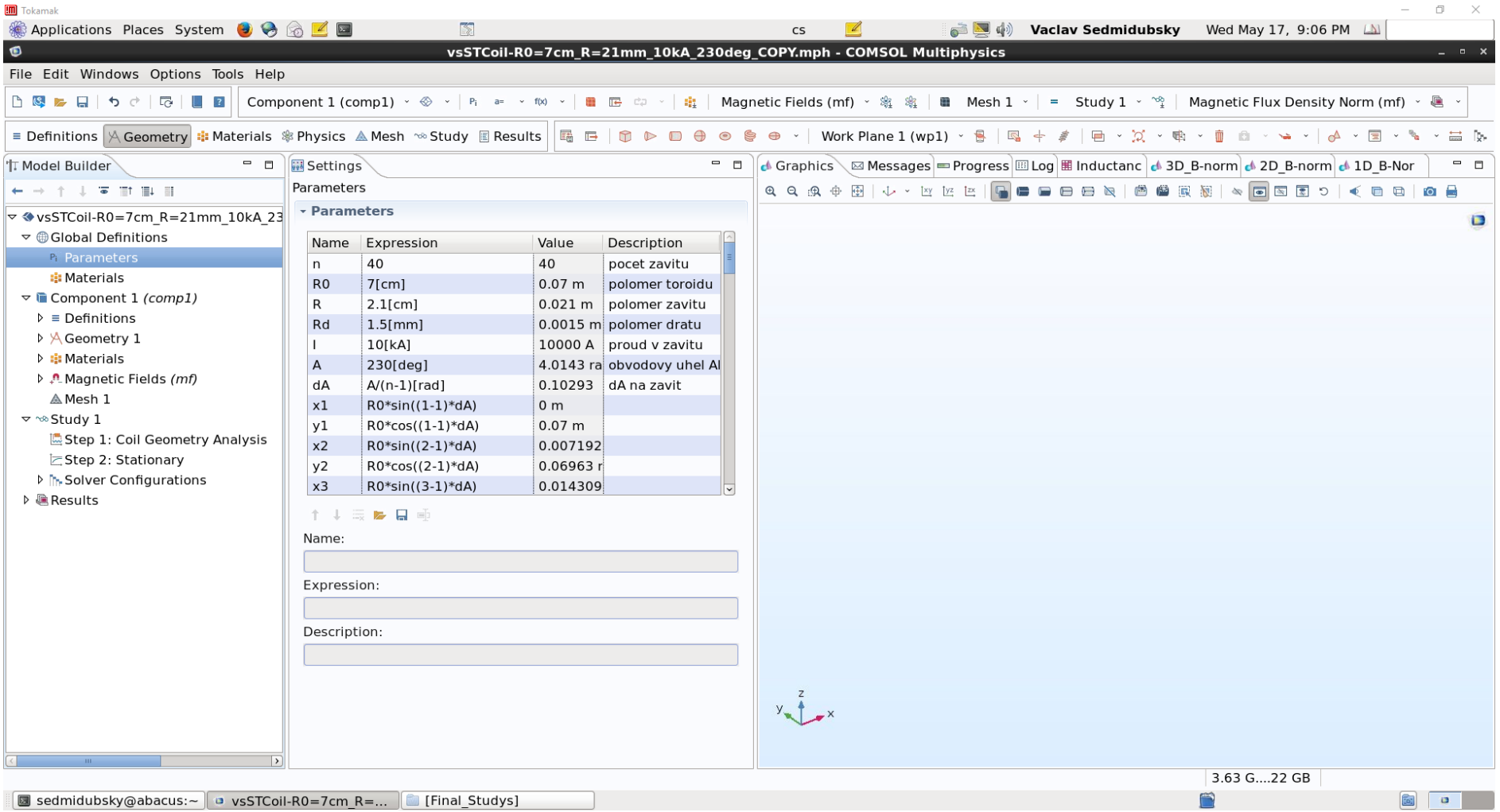
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Component 1 (comp1)
Magnetic Fields (mf)
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Study 1
Magnetic Flux Density Norm (mf)
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Work Plane 1 (wp1)
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Parameters
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Definitions
Geometry 1
Materials
Magnetic Fields (mf)
Mesh 1
Study 1
Step 1: Coil Geometry Analysis
Step 2: Stationary
Solver Configurations
Results
Settings
Parameters
Parameters
Name Expression Value Description
n 40 40 pocet zavitu
R0 7[cm] 0.07 m polomer toroidu
R 2.1[cm] 0.021 m polomer zavitu
Rd 1.5[mm] 0.0015 m polomer dratu
I 10[kA] 10000 A proud v zavitu
A 230[deg] 4.0143 ra obvodovy uhel Al
dA A/(n-1)[rad] 0.10293 dA na zavit
x1 R0*sin((1-1)*dA) 0 m
y1 R0*cos((1-1)*dA) 0.07 m
x2 R0*sin((2-1)*dA) 0.007192
y2 R0*cos((2-1)*dA) 0.06963 r
x3 R0*sin((3-1)*dA) 0.014309
Name:
Expression:
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3D_B-norm
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1D_B-Nor
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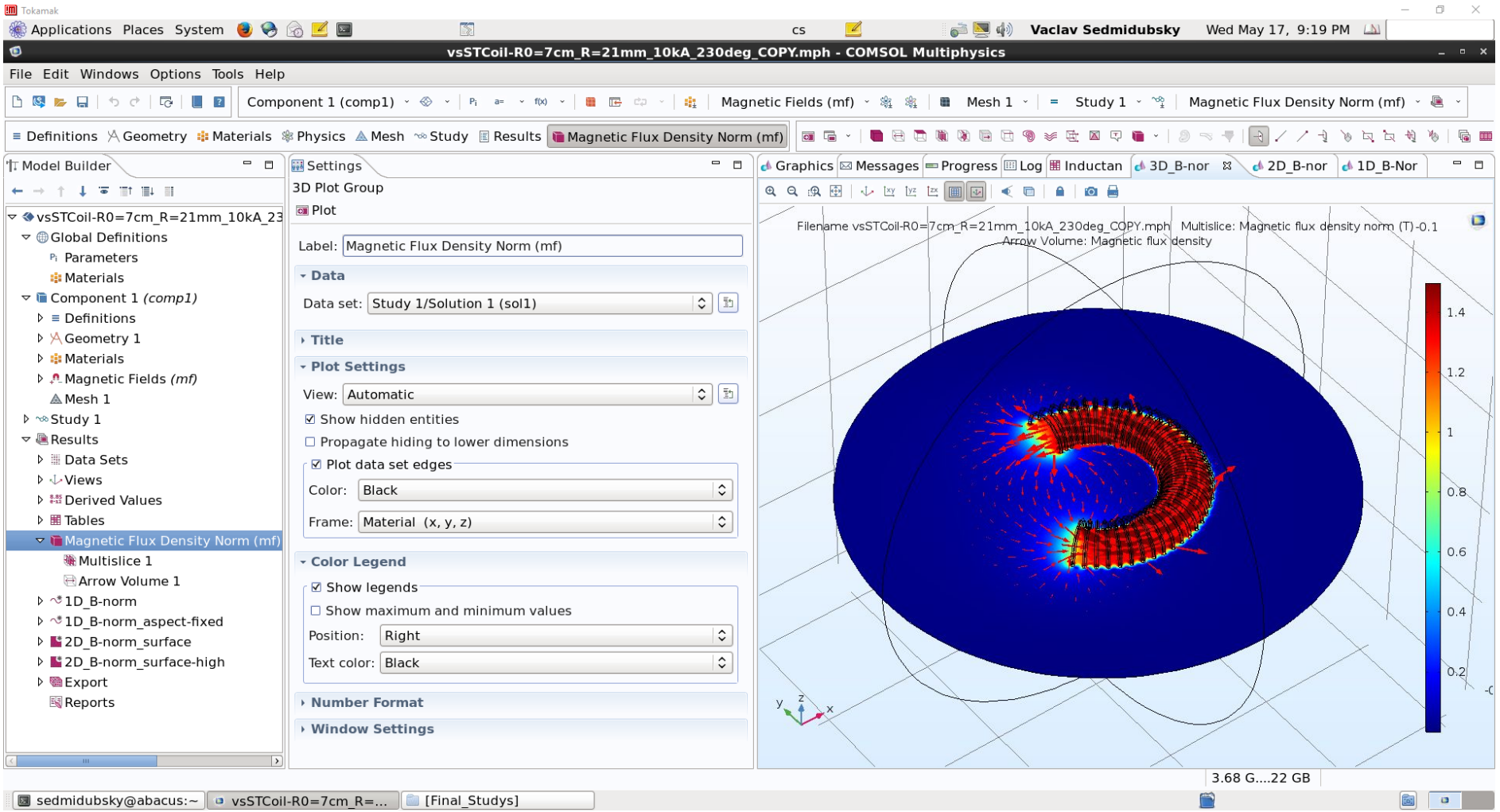
Tokamak
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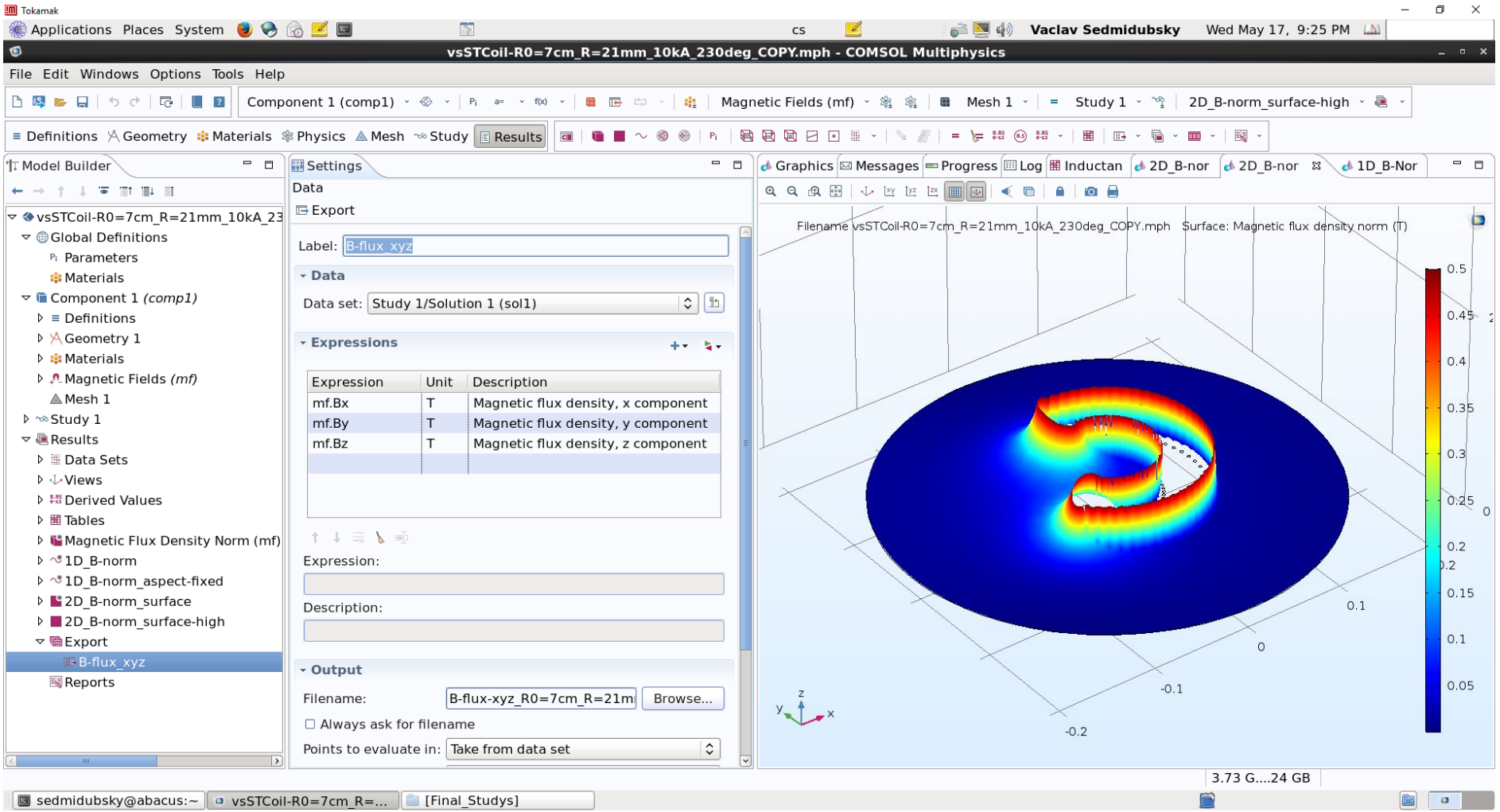
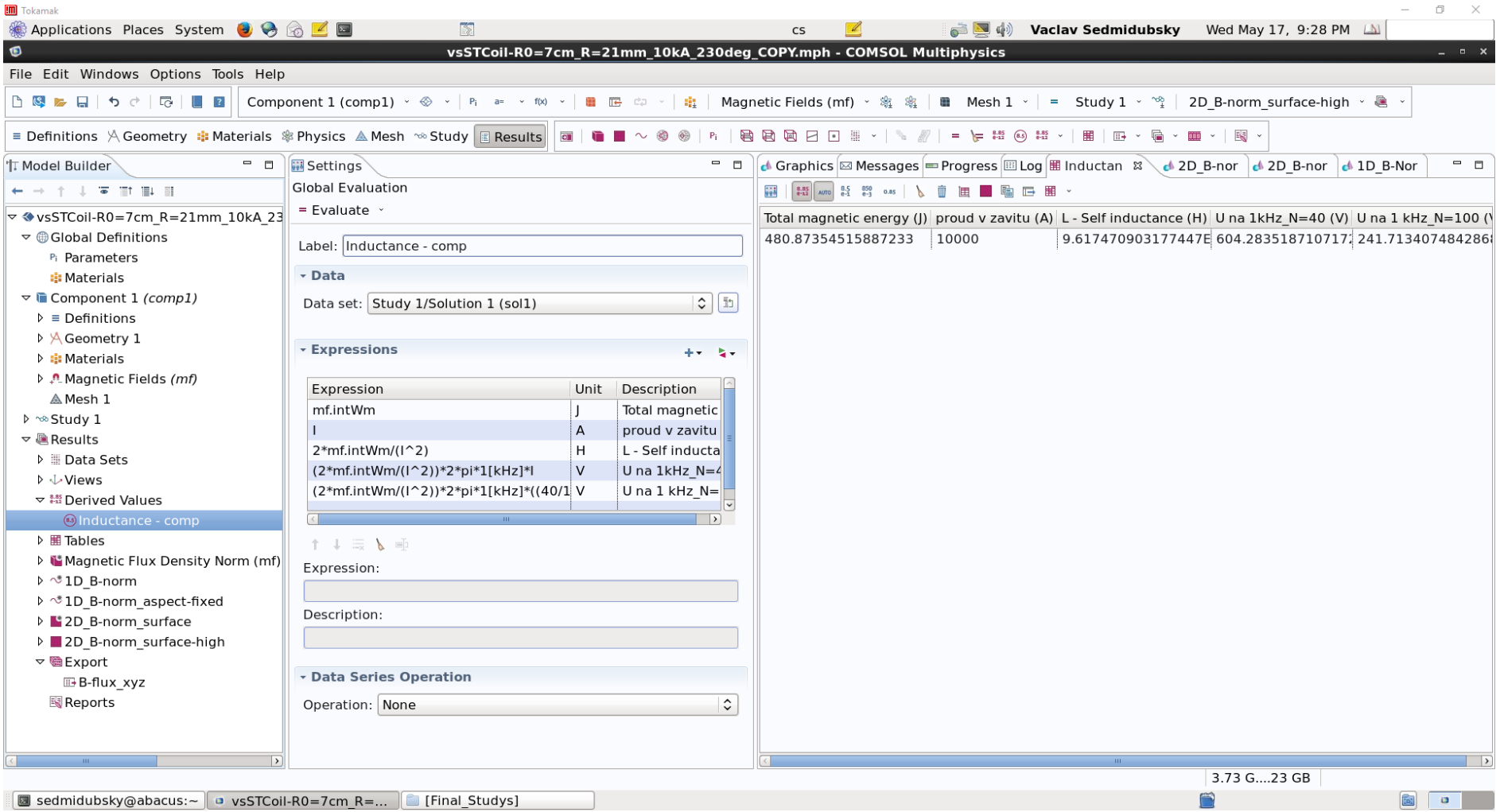
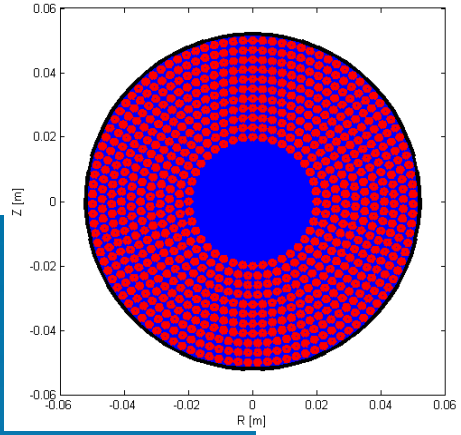
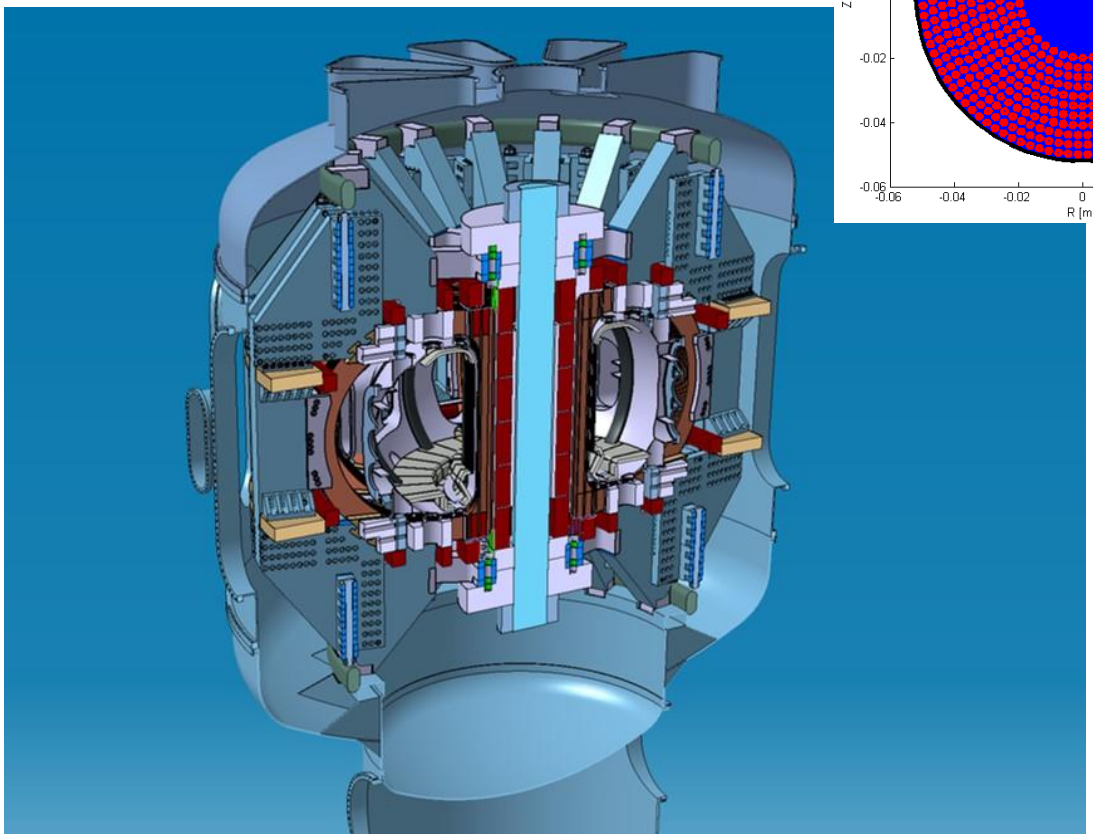
Parameters
Materials
Component 1 (comp1)
Definitions
Geometry 1
Materials
Magnetic Fields (mf)
Mesh 1
Study 1
Results
Data Sets
Views
Derived Values
Tables
Magnetic Flux Density Norm (mf)
Multislice 1
Arrow Volume 1
1D_B-norm
1D_B-norm_aspect-fixed
2D_B-norm_surface
2D_B-norm_surface-high
Export
Reports
Settings
3D Plot Group
Plot
Label: Magnetic Flux Density Norm (mf)
Data
Data set: Study 1/Solution 1 (sol1)
Title
Plot Settings
View: Automatic
Show hidden entities
Propagate hiding to lower dimensions
Plot data set edges
Color: Black
Frame: Material (x, y, z)
Color Legend
Show legends
Show maximum and minimum values
Position: Right
Text color: Black
Number Format
Window Settings
Graphics Messages Progress Log Inductan 3D_B-nor 2D_B-nor 1D_B-Nor
Filename vsSTCoil-R0=7cm_R=21mm_10kA_230deg_COPY.mph Multislice: Magnetic flux density norm (T) -0.1
Arrow Volume: Magnetic flux density
1.4
1.2
1
0.8
0.6
0.4
0.2
3.68 G....22 GB
sedmidubsky@abacus:~
vsSTCoil-R0=7cm_R=...
[Final_Studys]

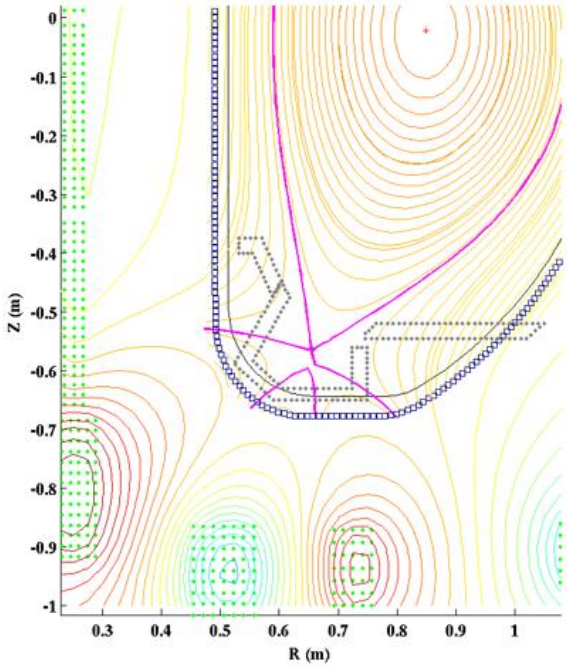

Tokamak
Applications Places System
Vaclav Sedmidubsky
Wed May 17, 9:25 PM
vsSTCoil-R0=7cm_R=21mm_10kA_230deg_COPY.mph - COMSOL Multiphysics
File Edit Windows Options Tools Help
Component 1 (comp1)
Magnetic Fields (mf)
Mesh 1
Study 1
2D_B-norm_surface-high
Definitions Geometry Materials Physics Mesh Study Results
Model Builder
vsSTCoil-R0=7cm_R=21mm_10kA_23
Global Definitions
Parameters
Materials
Component 1 (comp1)
Definitions
Geometry 1
Materials
Magnetic Fields (mf)
Mesh 1
Study 1
Results
Data Sets
Views
Derived Values
Tables
Magnetic Flux Density Norm (mf)
1D_B-norm
1D_B-norm_aspect-fixed
2D_B-norm_surface
2D_B-norm_surface-high
Export
B-flux_xyz
Reports
Settings
Data
Export
Label: B-flux_xyz
Data
Data set: Study 1/Solution 1 (sol1)
Expressions
Expression Unit Description
mf.Bx T Magnetic flux density, x component
mf.By T Magnetic flux density, y component
mf.Bz T Magnetic flux density, z component
Expression:
Description:
Output
Filename: B-flux-xyz_R0=7cm_R=21m
Browse...
Always ask for filename
Points to evaluate in: Take from data set
Graphics Messages Progress Log Inductan 2D_B-nor 2D_B-nor 1D_B-Nor
Filename vsSTCoil-R0=7cm_R=21mm_10kA_230deg_COPY.mph Surface: Magnetic flux density norm (T)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0.1
0
-0.1
-0.2
z
y
x
3.73 G....24 GB
sedmidubsky@abacus:~
vsSTCoil-R0=7cm_R=...
[Final_Studys]

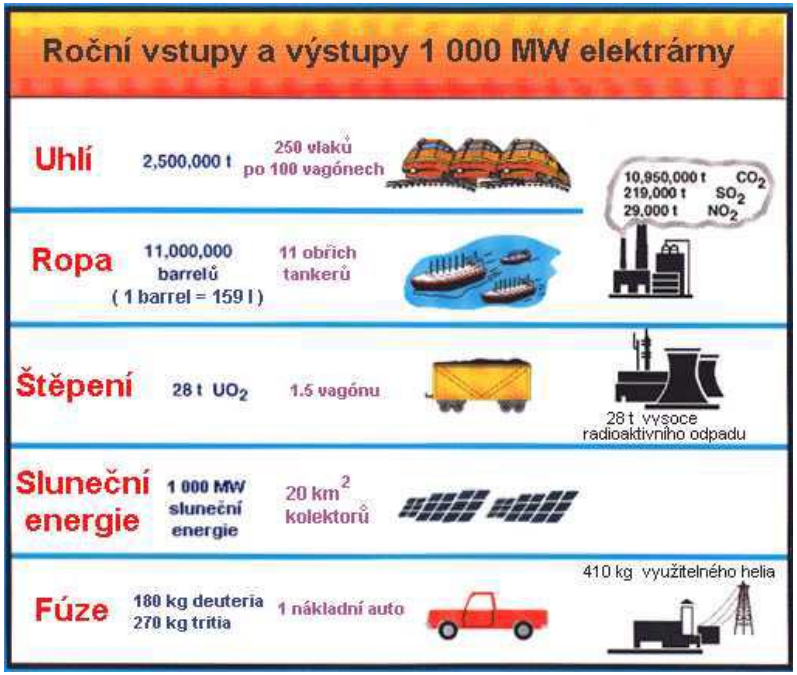

Tokamak
Applications Places System
cs
Vaclav Sedmidubsky
Wed May 17, 9:28 PM
vsSTCoil-R0=7cm_R=21mm_10kA_230deg_COPY.mph - COMSOL Multiphysics
File Edit Windows Options Tools Help
Component 1 (comp1)
Magnetic Fields (mf)
Mesh 1
Study 1
2D_B-norm_surface-high
Definitions Geometry Materials Physics Mesh Study Results
Model Builder
vsSTCoil-R0=7cm_R=21mm_10kA_23
Global Definitions
Parameters
Materials
Component 1 (comp1)
Definitions
Geometry 1
Materials
Magnetic Fields (mf)
Mesh 1
Study 1
Results
Data Sets
Views
Derived Values
Inductance - comp
Tables
Magnetic Flux Density Norm (mf)
1D_B-norm
1D_B-norm_aspect-fixed
2D_B-norm_surface
2D_B-norm_surface-high
Export
B-flux_xyz
Reports
Settings
Global Evaluation
Evaluate
Label: Inductance - comp
Data
Data set: Study 1/Solution 1 (sol1)
Expressions
Expression Unit Description
mf.intWm J Total magnetic
I A proud v zavitu
2*mf.intWm/(I^2) H L - Self inducta
(2*mf.intWm/(I^2))*2*pi*1[kHz]*I V U na 1kHz_N=
(2*mf.intWm/(I^2))*2*pi*1[kHz]*((40/1 V U na 1 kHz_N=
Expression:
Description:
Data Series Operation
Operation: None
Graphics Messages Progress Log Inductan 2D_B-nor 2D_B-nor 1D_B-Nor
Total magnetic energy (J) proud v zavitu (A) L - Self inductance (H) U na 1kHz_N=40 (V) U na 1 kHz_N=100 (V
480.87354515887233 10000 9.617470903177447E 604.2835187107171 241.71340748428
3.73 G....23 GB
sedmidubsky@abacus:~
vsSTCoil-R0=7cm_R=...
[Final_Studys]

- **dynamická studie vířivých proudů** na divertorové desce tokamaku DEMO vytvořené C-cívkou (aktuálně probíhá) + optimalizace parametrů C-cívky
- divertor z tekutých kovů (Li, Sn, …)
- Litzovo vlákno „Litz-wire“ - thermal transfer
- COMPASS-Upgrade
  - CAD geometry import
  - Structural mechanics module
  - Thermal transfer module

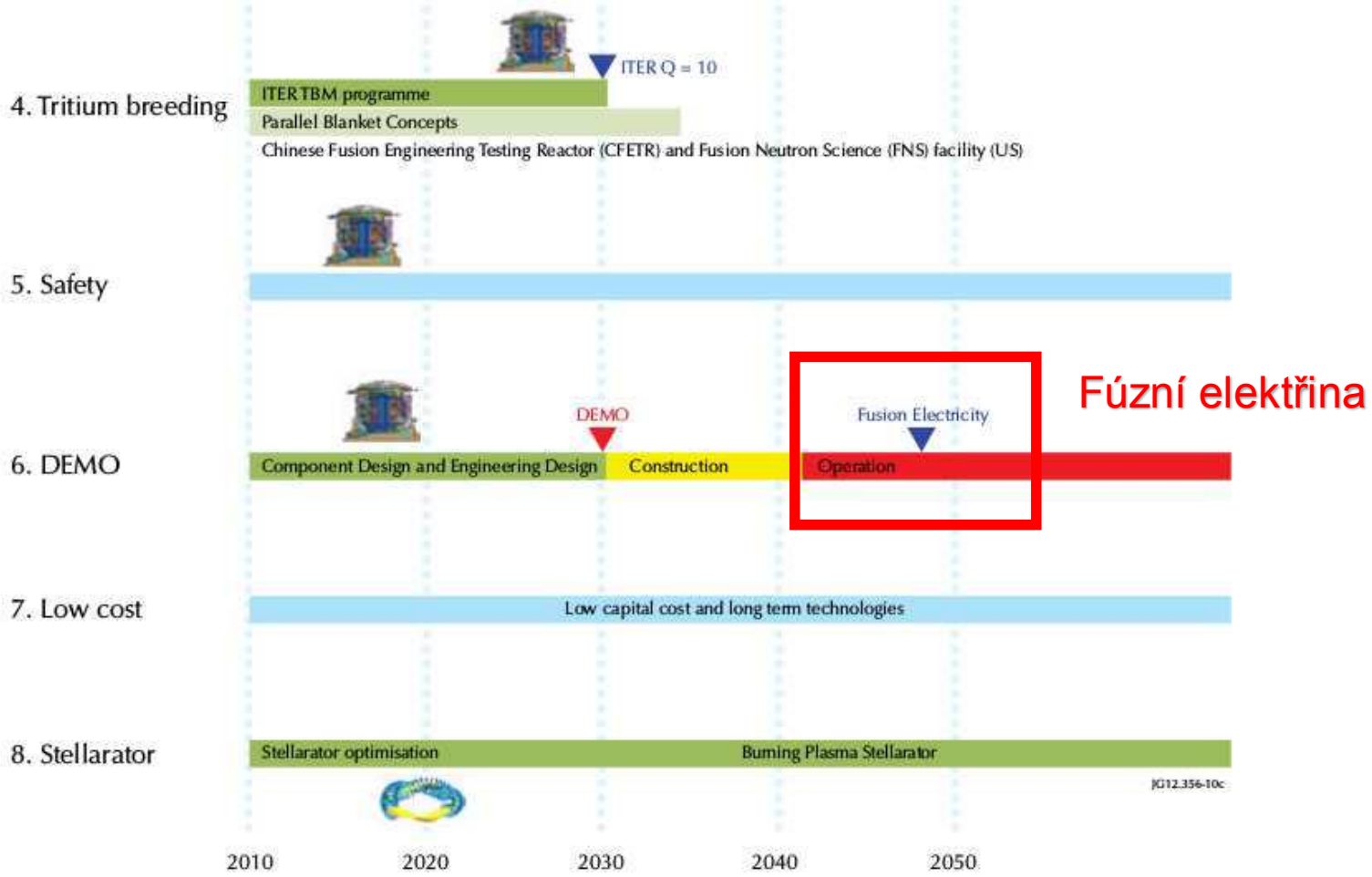







Roční vstupy a výstupy 1 000 MW elektrárny
Uhlí
2,500,000 t
250 vlaků po 100 vagónech
10,950,000 t CO_2
219,000 t SO_2
29,000 t NO_2
Ropa
11,000,000 barrelů (1 barrel = 159 l)
11 obřích tankerů
Štěpení
28 t UO_2
1.5 vagónu
28 t vysoce radioaktivního odpadu
Sluneční energie
1 000 MW sluneční energie
20 km^2 kolektorů
Fúze
180 kg deuteria
270 kg tritia
1 nákladní auto
410 kg využitelného helia

Energetická nezávislost do 40 let?



Fúzní elektřina

Zdroje

- **Mgr. Jan Horaček, dr. es sc. -** prezentace „Současný český a mezinárodní výzkum nevyčerpatelného zdroje bezpečné termojaderné energie: proč, jak, kdy, za kolik?"
- www.ipp.cas.cz
- http://www.iter.org/