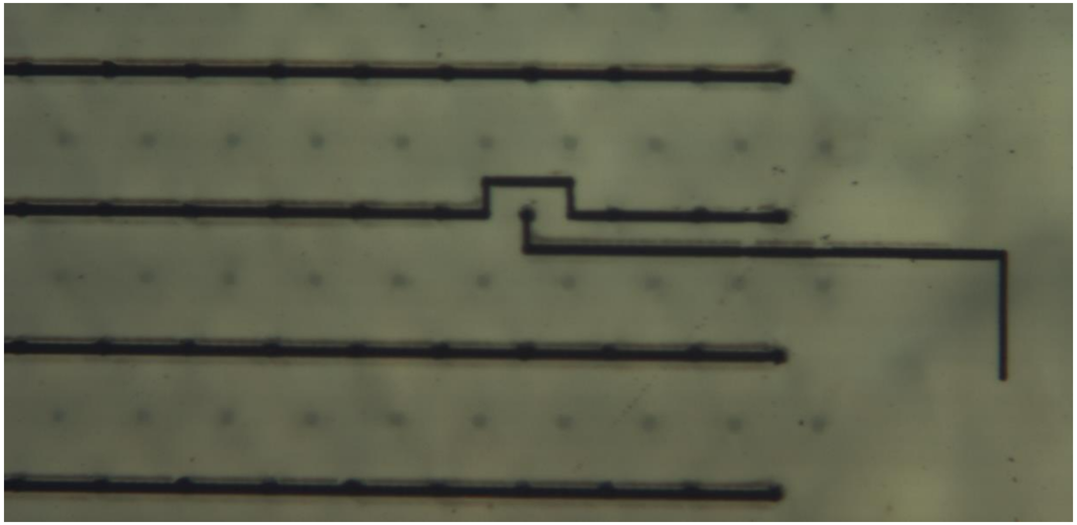
Advances in 3D diamond detectors fabrication and tests in Florence



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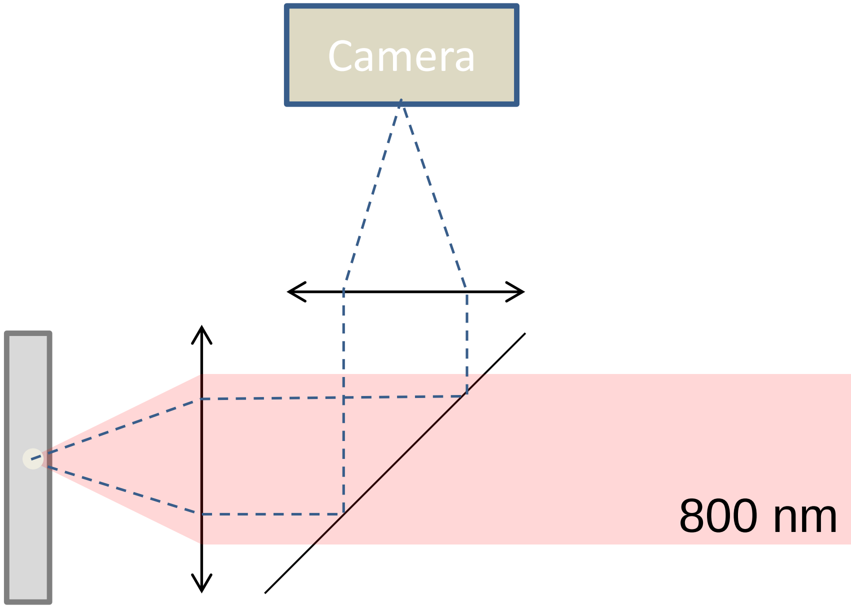
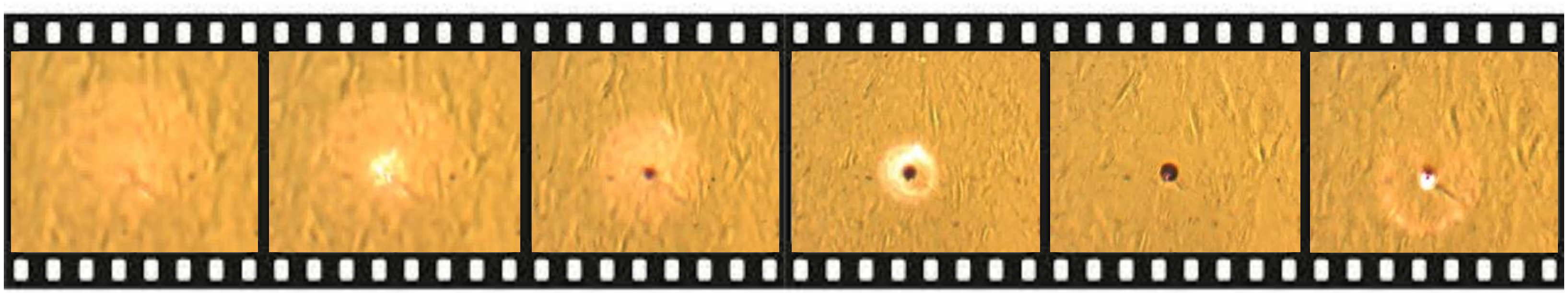
The 3D fabrication facility in Florence employs two integrated laser systems:



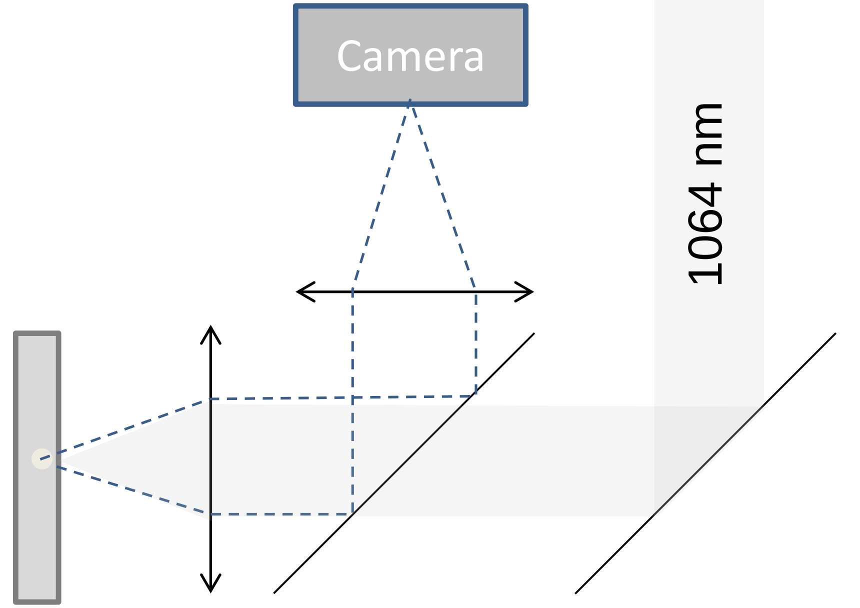
1) An 800 nm, 25÷70 fs pulsed Ti:Saffire laser integrated with A confocal visualization system (position control <5 μm xy, ~20 μm z)



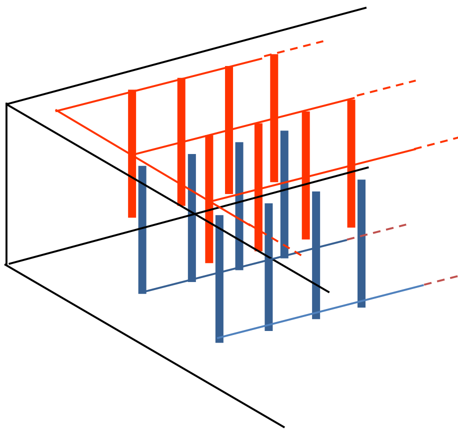
Resistivity of the modified materials ≈ 0.5 - 1 Ωcm

We employed two integrated laser systems:

1) An 800 nm, 30 fs pulsed Ti:Saffire laser integrated with A confocal visualization system (control the columns lenght with a 10-20 μm resolution)

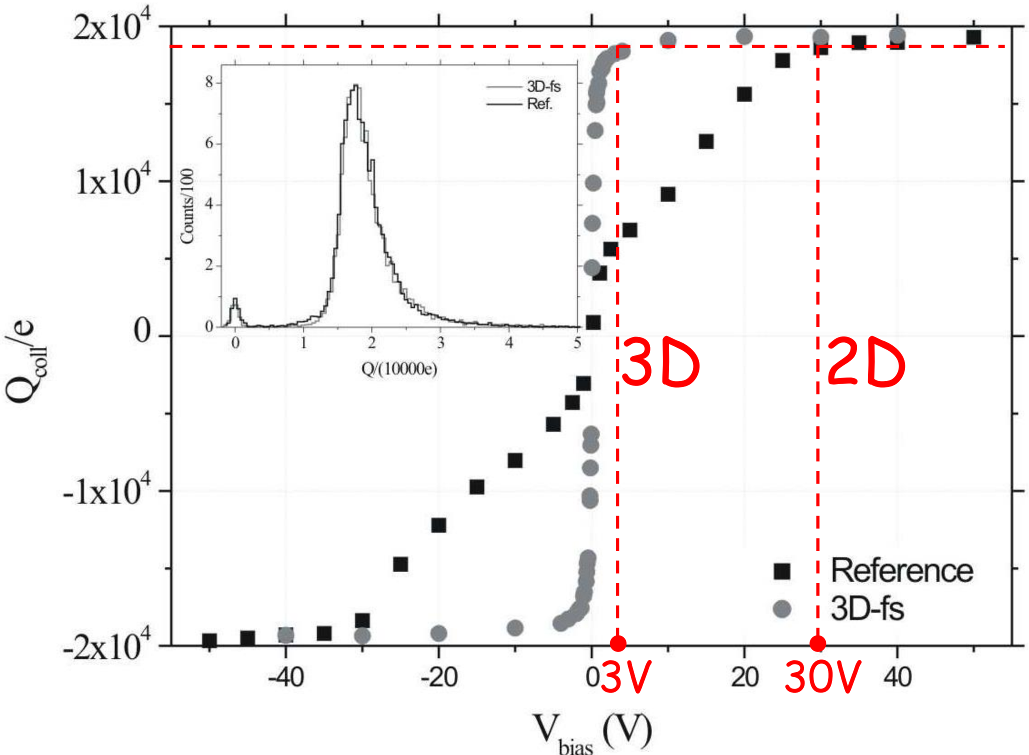


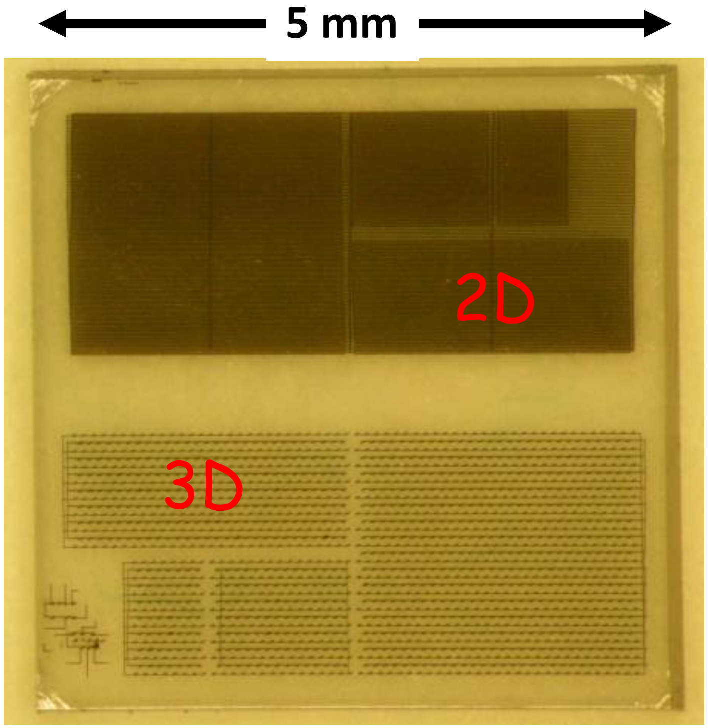
2) An alternative line for the micro-writing of superficial graphitic wires (Nd:YAG, 8 ns pulse duration)



Resistivity ≈ 0.03 Ωcm (amorphous graphite)

The 3D single crystal sensors exhibited of full collection for β-induced signal
at 3 V of bias, 1 order of magnitude less than the conventiona
planar detectors fabricated for reference





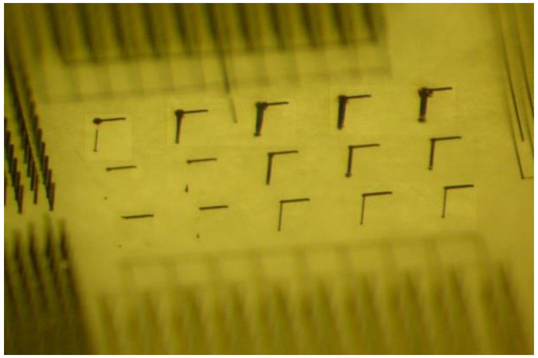
Mean signal ≈ 20000 e (at 3V bias);
Noise ≈ 300 e (1 μs int. time)

S/N ratio ≈ 70

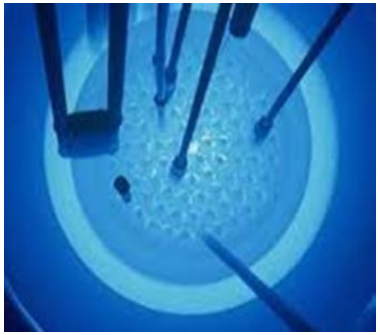
Three-dimensional diamond detectors: Charge collection efficiency of graphitic electrodes S Lagomarsino, M Bellini, C Corsi, F Gorelli, G Parrini, M Santoro, S Sciortino. Applied Physics Letters 103 (2013) 233507

The Florence group activity in 3D diamond fabrication and characterization of the last year:

A study of the quality of the conductive columns in dependence on the processing parameters (pulse energy and lenght)



A study on the radiation hardness of 3D polycristalline, single-crystal and DOI diamond sensors under neutron irradiation.

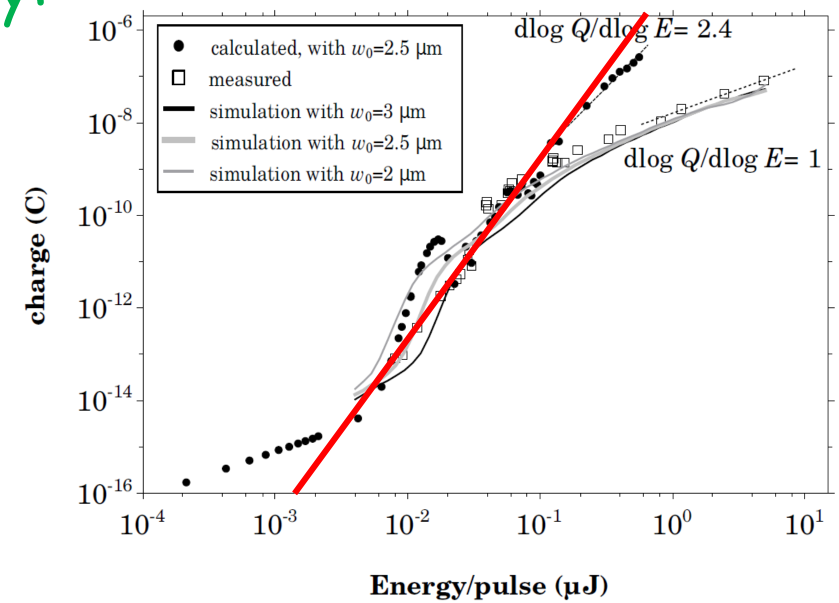


A study of the quality of the conductive columns in dependence on the processing parameters (pulse energy and lenght)

Two orders of reasons for such a study

1) A question of reproducibility:

The rate of generation of the charge carriers in the waist of the laser beam was found* to be proportional to the 4th power of the intensity due to multi-photon absorption: $dQ/dt \approx I^4$



* Photoionization of monocrystalline CVD diamond irradiated with ultra-short intense laser pulses
S.Lagomarsino, S.Sciortino et al. Submitted to Phys. Rev. B

But, if $Q = dQ/dt \times\tau \approx (E/\tau)^4 \times \tau = E^4/\tau^3$

Thus, a good control on the pulse duration τ is essential for the reproducibility.

A study of the quality of the conductive columns in dependence on the processing parameters (pulse energy and lenght)

Two orders of reasons for such a study

1) A question of reproducibility:

$$\text{But, if } Q = dQ/dt \times \tau \approx (E/\tau)^4 \times \tau = E^4/\tau^3$$

2) In view of a forthcoming upgrade

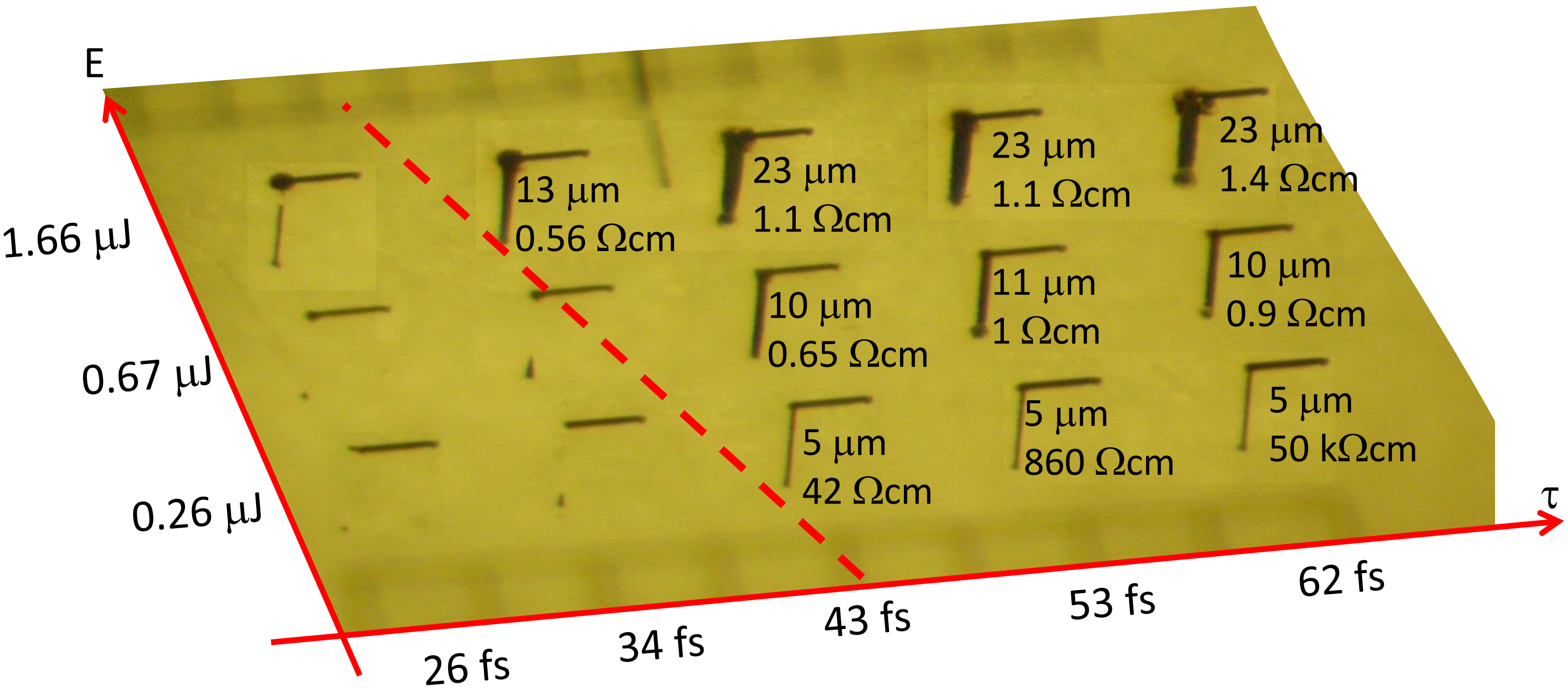
We are planning to implement two new features

1) A new 20X, high luminosity, long working distance objective (instead of the present 10X)
2) An adaptive mirror for spherical aberration correction*

* High conductivity microwires in diamond following arbitrary paths B. Sun et al APL 105 (2014) 231105

Both should require suitable adjustments in the beam parameters to obtain optimal results.

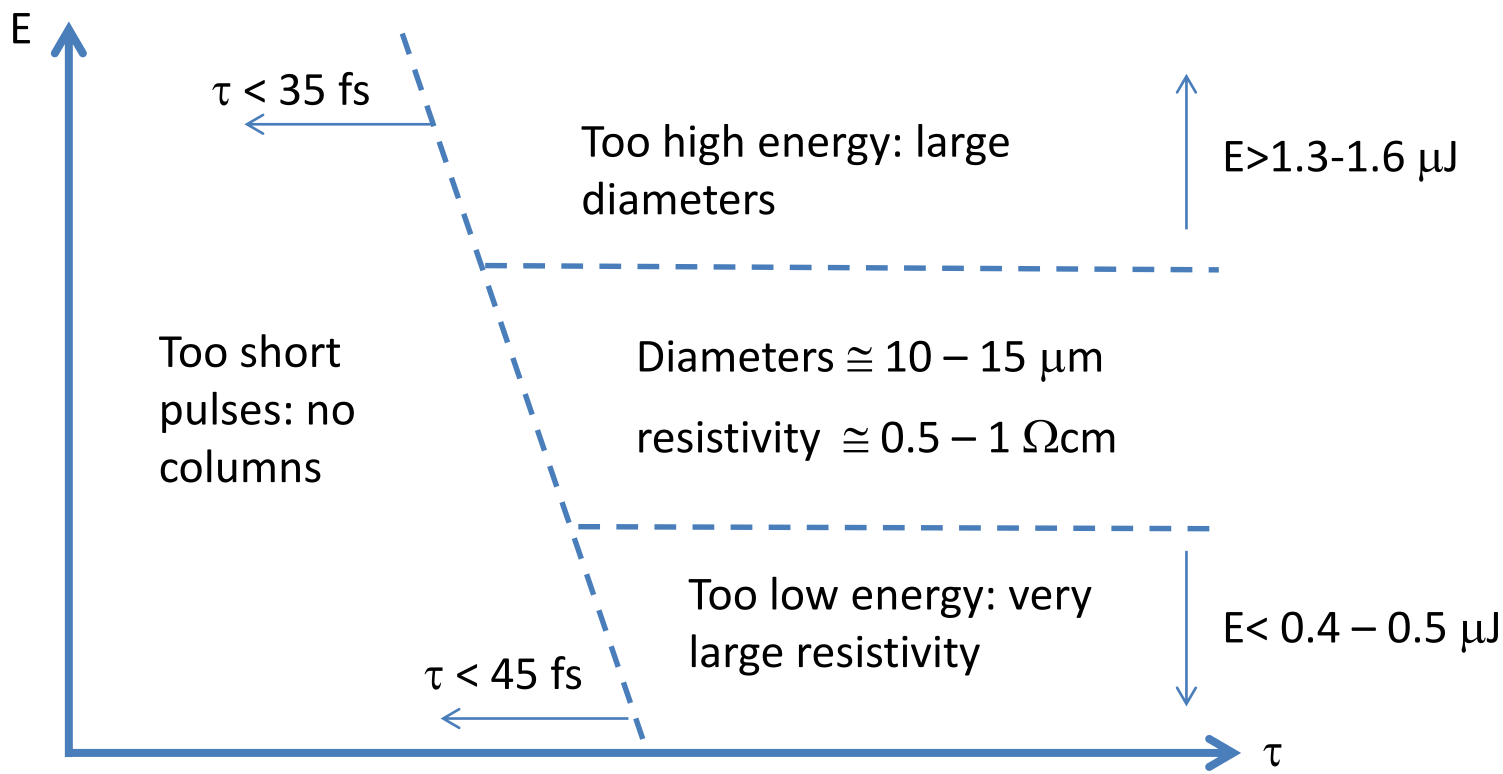
At any given pulse energy E, there is a minimum pulse lenght τ_{min} below which graphitization does not occur at all



Above τ_{min}, it seems to be an optimal pulse duration in term of material resistivity, above which the resistivity increases

Below a given energy, column diameter can be very small, but column resistances become too high.

A sort of phase diagram for graphitic columns fabrication::

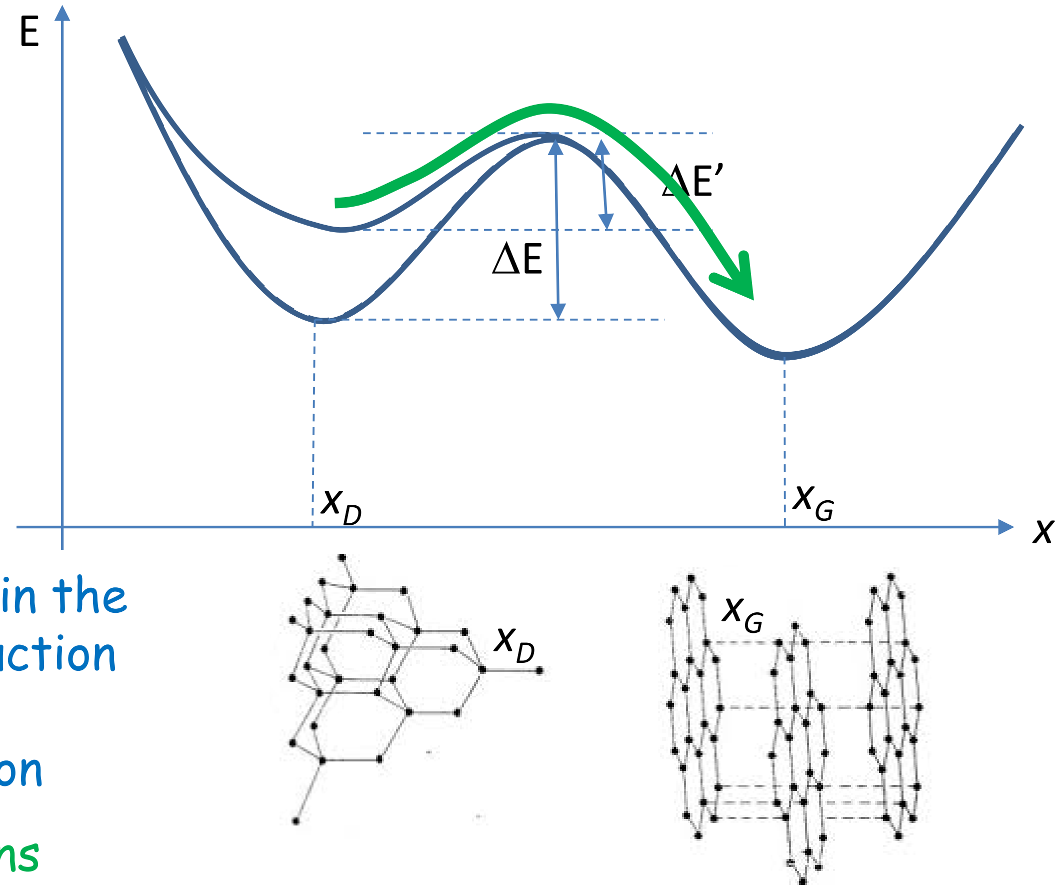


The diagram depends also on the numerical aperture of the objective (0.24 in our case) and on the spatial spectrum of the beam.

We can propose a rationale for the counter-intuitive lower threshold to the pulse duration.

We can propose a rationale for the counter-intuitive lower lower threshold to the pulse duration.

Diamond-graphite phase transformation is governed by the height of the energy barrier between sp^3 and sp^2 bonding*.



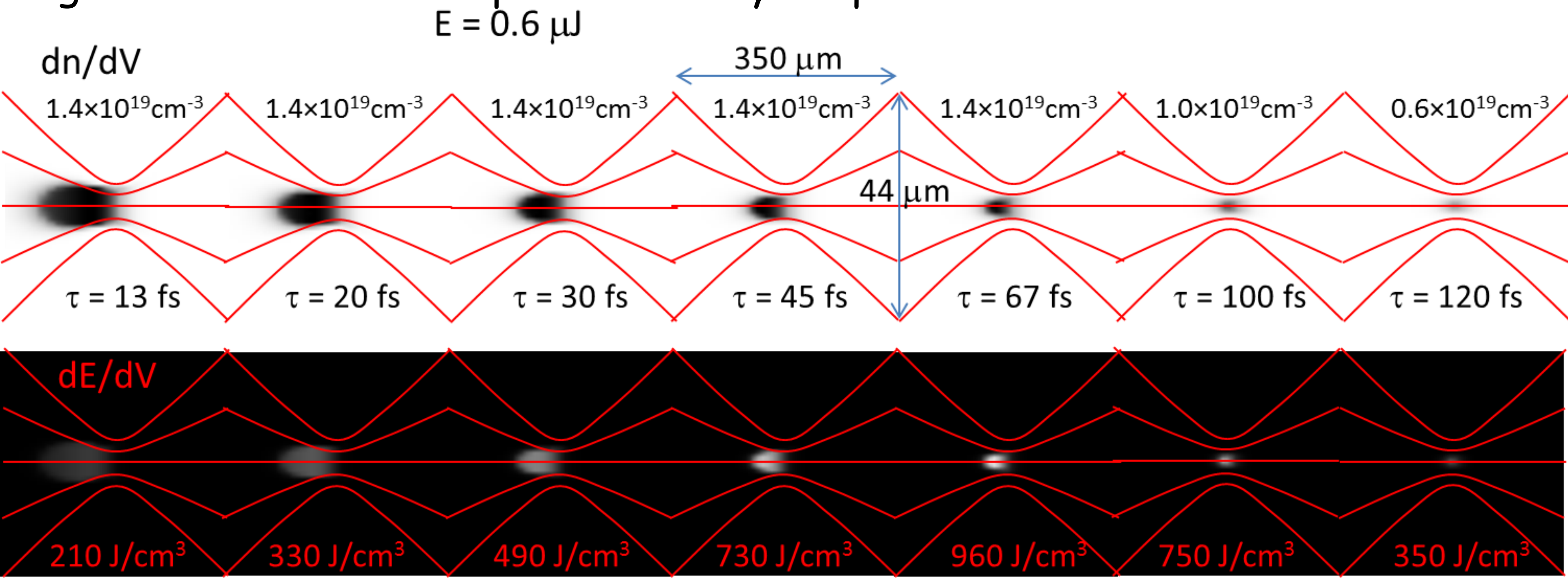
The more electrons are excited in the anti-bonding states of the conduction band, the lower is such barrier, promoting sp3-sp2 transformation

Moreover, the higher the electrons temperature, the easier for the lattice to overtake the residual energy barrier.

*H.O. Jeschke et al. Microscopic analysis of the laser-induced femtosecond graphitization of diamond. PRB 60 (1999) R3701

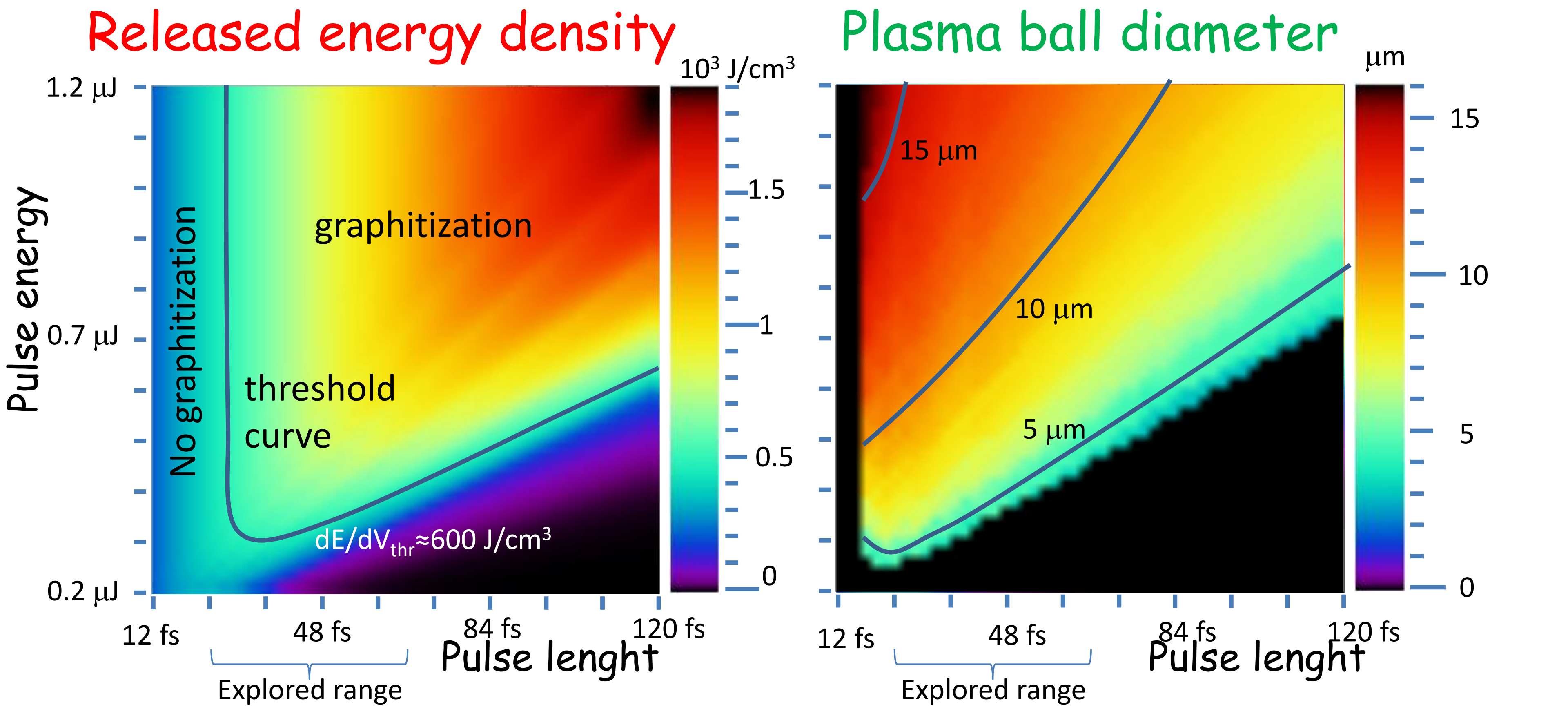
So the phase transformation is governed by both density and temperature of the plasma generated by laser irradiation.

According to our calculations of the plasma density and energy distribution, at high intensities, the plasma becomes opaque, and the radiation heats the already generated distribution instead of generate new e-h couples in the layers placed behind.



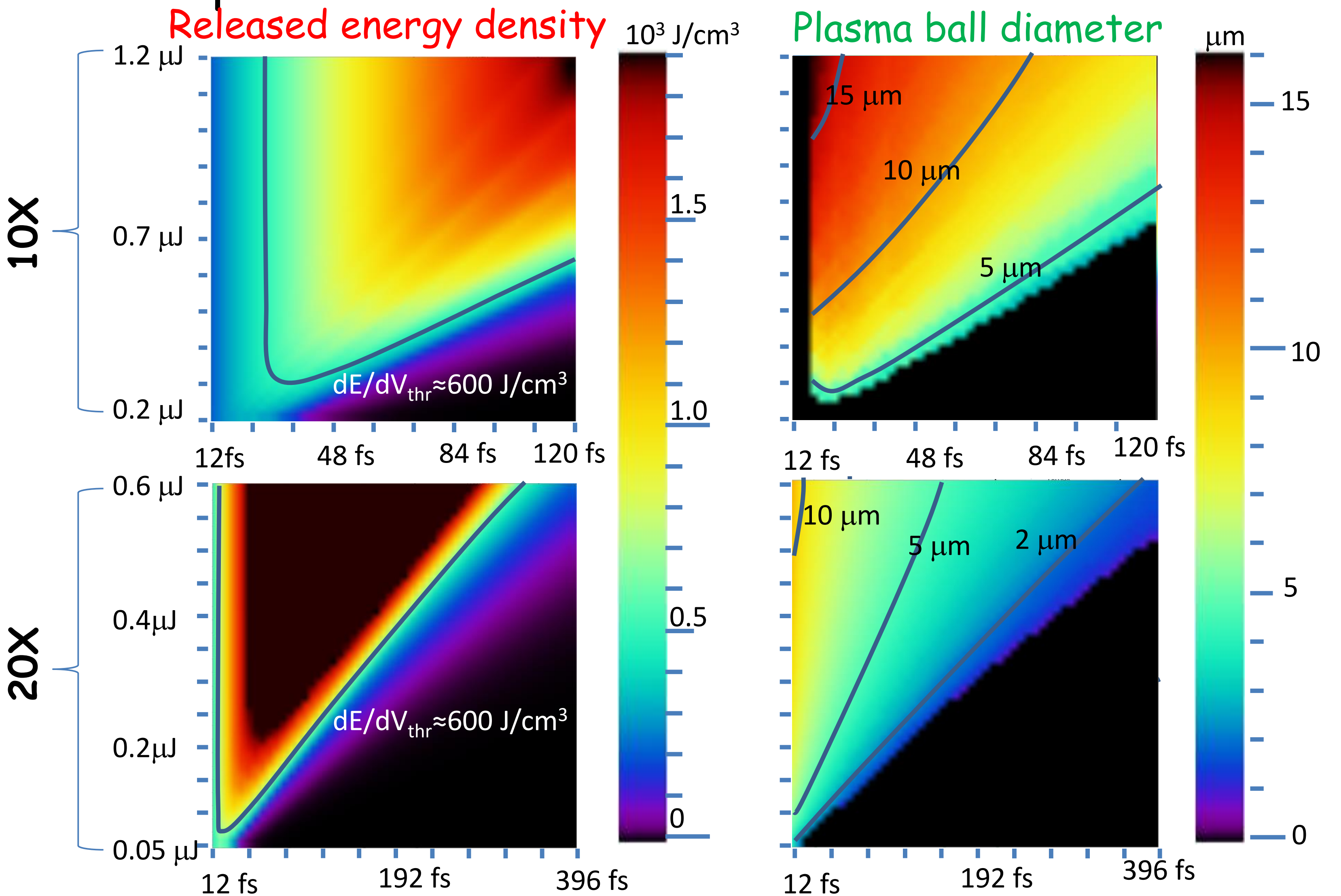
Notwithstanding the plasma density of the adsorbing layer is quite the same for all pulse durations, the plasma temperature decreases for shorter pulses, because the volume increases and the released energy density decreases.
So, for too short pulses the energy density does not reach the minimum value necessary for the phase transition to occur
As a consequence, at the same pulse energy, for shorter and shorter pulses, the absorbing layer moves backwards and backwards, maintaing a same maximum plasma density.

Combining the calculation both of the maximum released energy density and of the diameter of the plasma ball, we can identify an «allowed window» in the E-τ space, for the fabrication of graphitic columns with suitable characteristics.



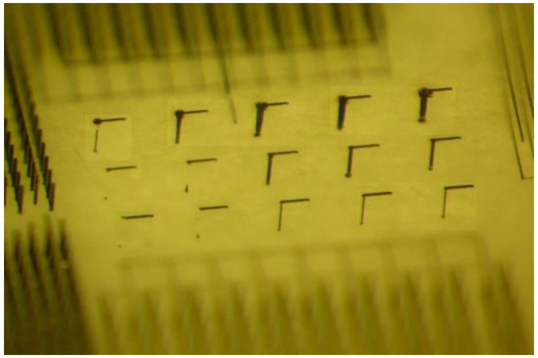
The «allowed» window in the E-τ diagram is also limited for long τ, but the forbidden values are not accessible with our system

The allowed window depends of course on the characteristics of the optics: a comparation between our 10X optics and a 20X one:



Higher values of τ are allowed at lower pulse energies

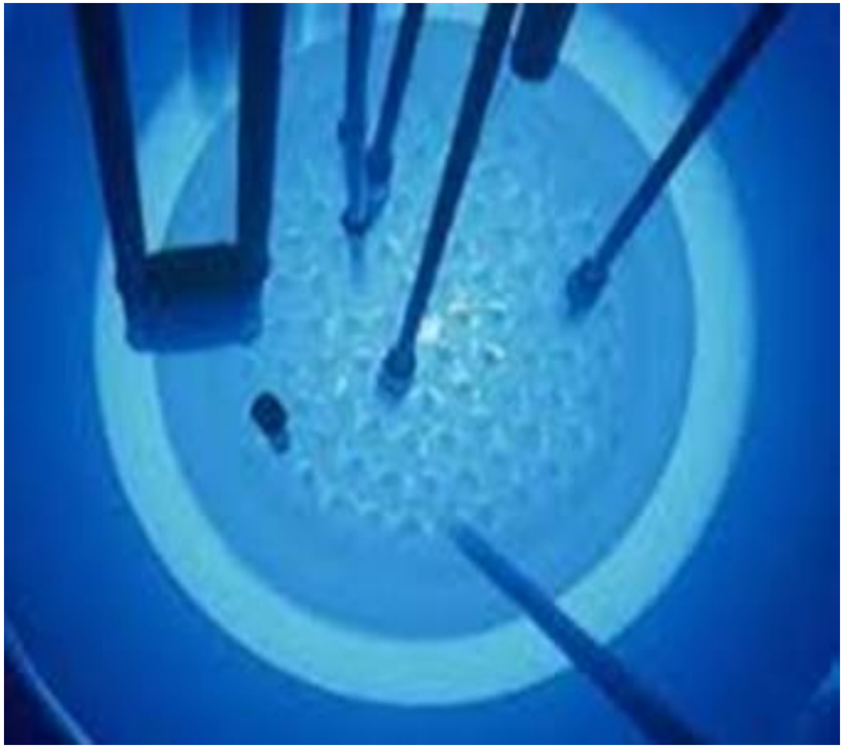
A study of the quality of the conductive columns in dependence on the processing parameters (pulse energy and lenght)



1) Now we are able to control both energy and lenght of the pulse duration, in order to improve the reproducibility of the results in term of diameter and conductance of the graphitic columns.

2) Once given the characteristics of the optics, we have theoretical instruments to guess the optimal beam parameters.

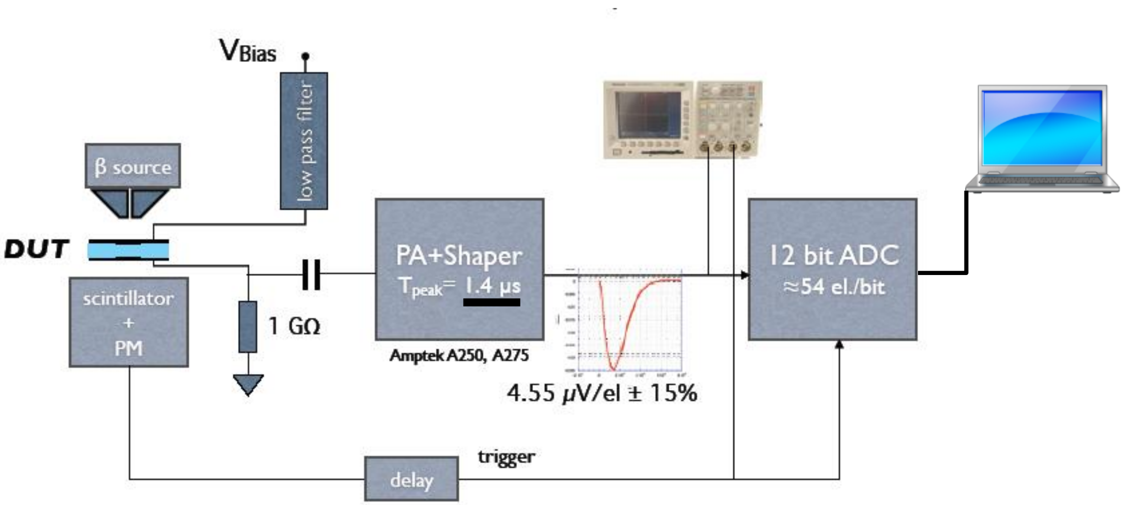
A study on the radiation hardness of 3D polycristalline, single-crystal and DOI diamond sensors under neutron irradiation.



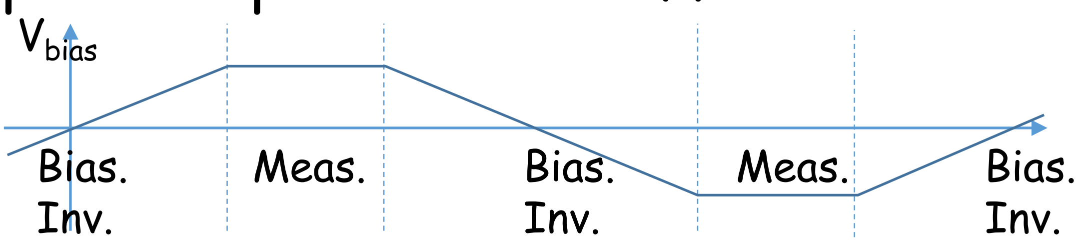
We planned a thorough investigation on the radiation hardness of several kind of 3D diamond sensors (500 μm thick):

	Homo-epitaxial		Highly-oriented		Poorly-oriented
E6	scCVD	Augsburg university	diamond-on-Iridium	E6	pCVD
LENS-Florence	2D (2) 3D 125 col/mm^2 (2) 3D 250 col/mm^2 (1) 3D 500 col/mm^2 (1)		2D (1) 3D 250 col/mm^2 (1)		2D (4) 3D 125 col/mm^2 (4) 3D 250 col/mm^2 (4)
JSI - Ljubljana	1.25×10^{15} ✓ 2.5×10^{15} ✓ 5×10^{15} 7.5×10^{15} 1×10^{16} 1MeV n/cm^2		 2.5×10^{15} ✓ 5×10^{15} 7.5×10^{15} 1×10^{16} 1MeV n/cm^2		 2.64×10^{14} ✓ 3×10^{15} ✓ 6×10^{15} ✓ 1.2×10^{16} ✓ 1MeV n/cm^2

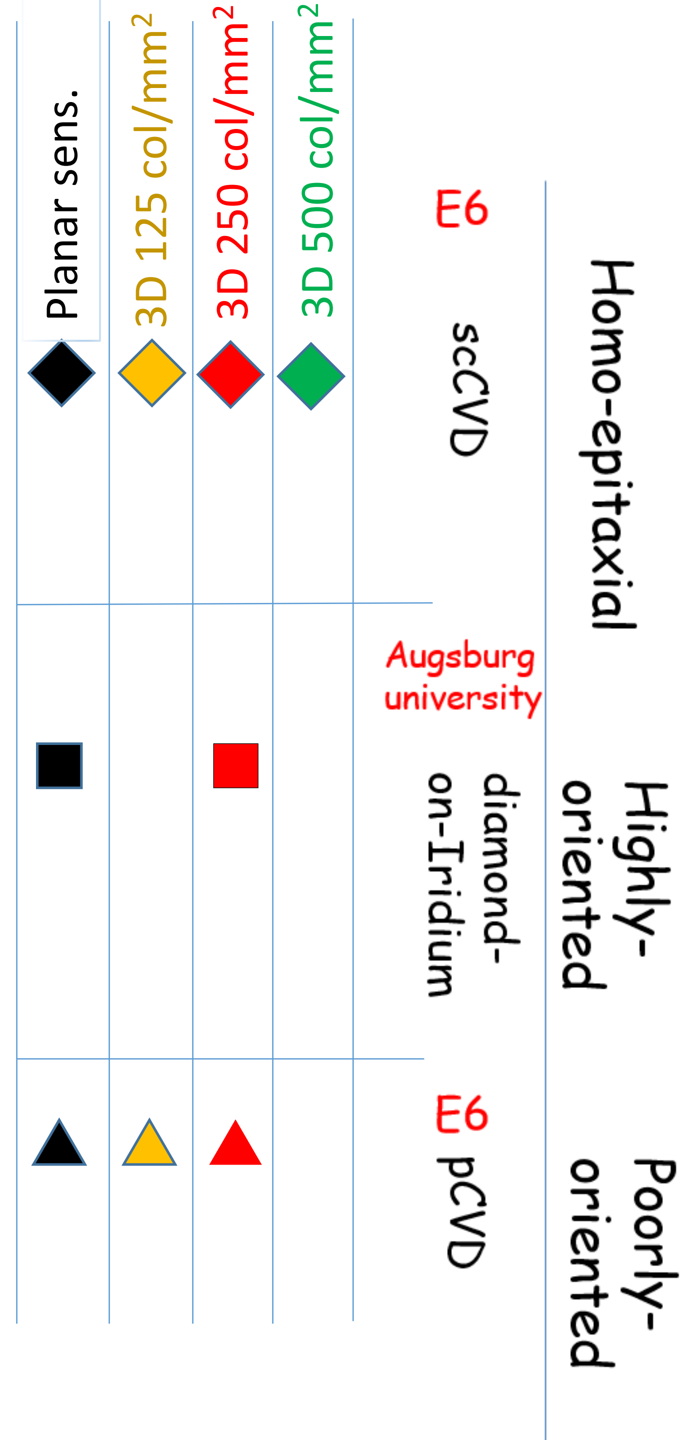
Measurements of the collected charge under ^{90}Sr beta irradiation has been carried out

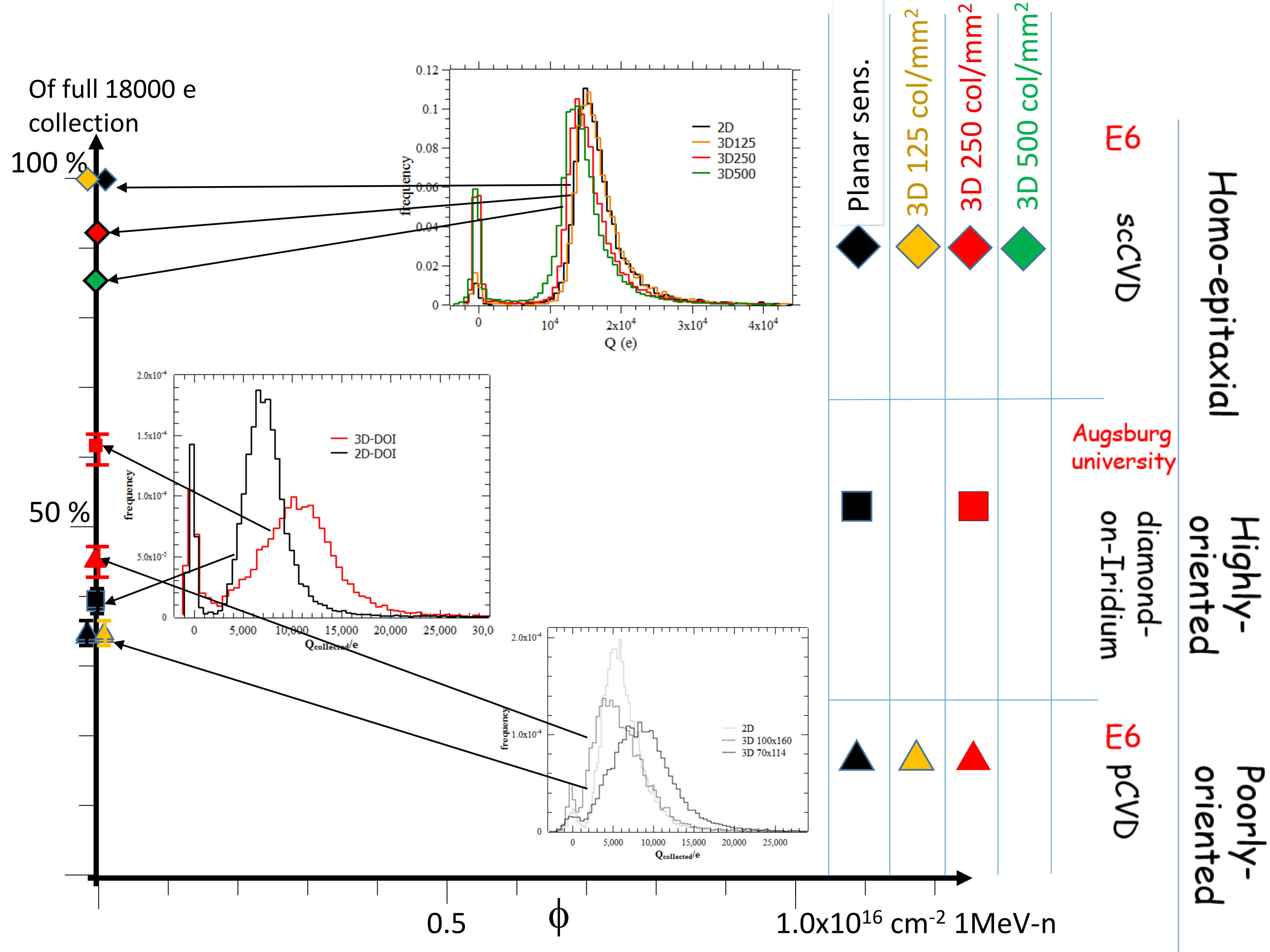


Bias was periodically inverted to prevent polarization effects

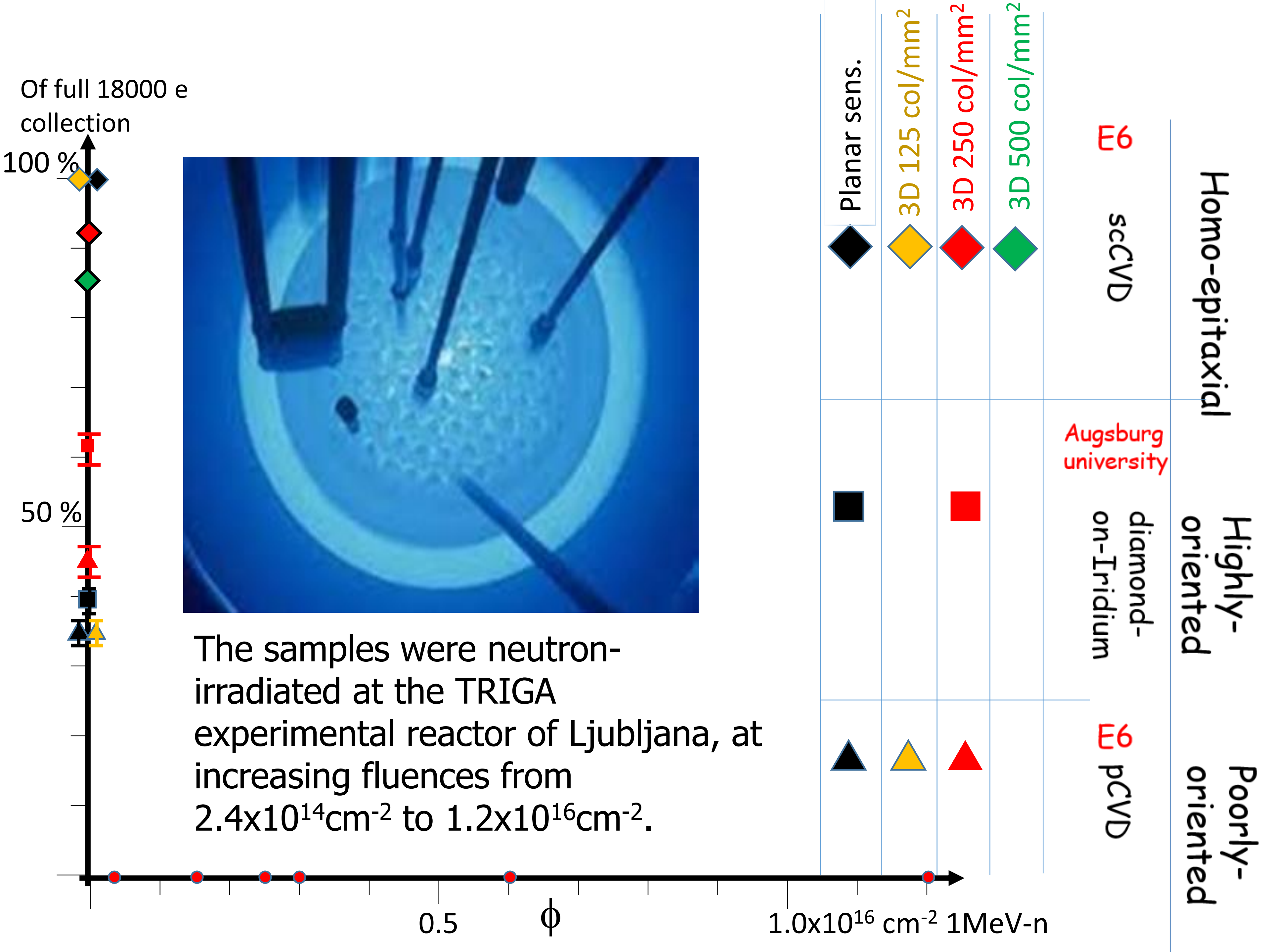


Which were anyway sensible only at low bias voltages

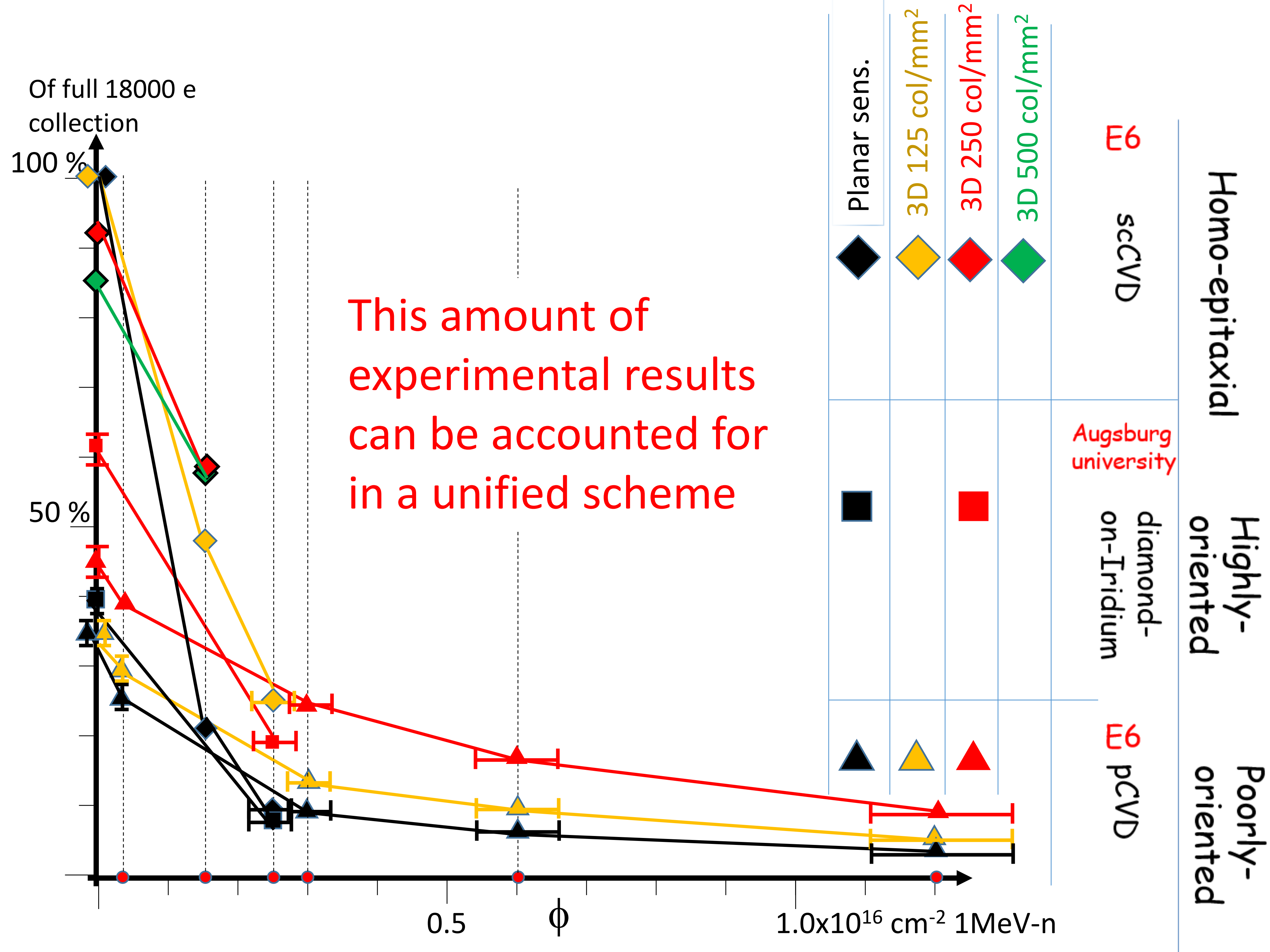




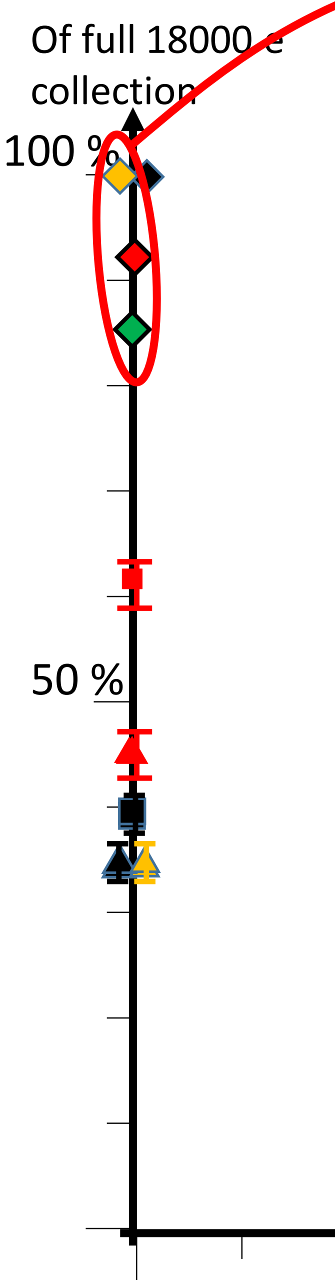
Of full 18000 e collection
100 %
50 %
0.5
ϕ
1.0x10^16 cm^-2 1MeV-n
2D
3D125
3D250
3D500
frequency
Q (e)
3D-DOI
2D-DOI
Qcollected/e
2D
3D 100x160
3D 70x114
Planar sens.
3D 125 col/mm²
3D 250 col/mm²
3D 500 col/mm²
E6
scCVD
Homo-epitaxial
Augsburg university
diamond-on-Iridium
Highly-oriented
E6
pCVD
Poorly-oriented



The samples were neutron-irradiated at the TRIGA experimental reactor of Ljubljana, at increasing fluences from $2.4 \times 10^{14} cm^{-2}$ to $1.2 \times 10^{16} cm^{-2}$.



Of full 18000 e collection
100 %
50 %
0.5
ϕ
1.0x10^16 cm^-2 1MeV-n
This amount of experimental results can be accounted for in a unified scheme
Planar sens.
3D 125 col/mm²
3D 250 col/mm²
3D 500 col/mm²
E6
scCVD
Homo-epitaxial
Augsburg university
diamond-on-Iridium
Highly-oriented
E6
pCVD
Poorly-oriented

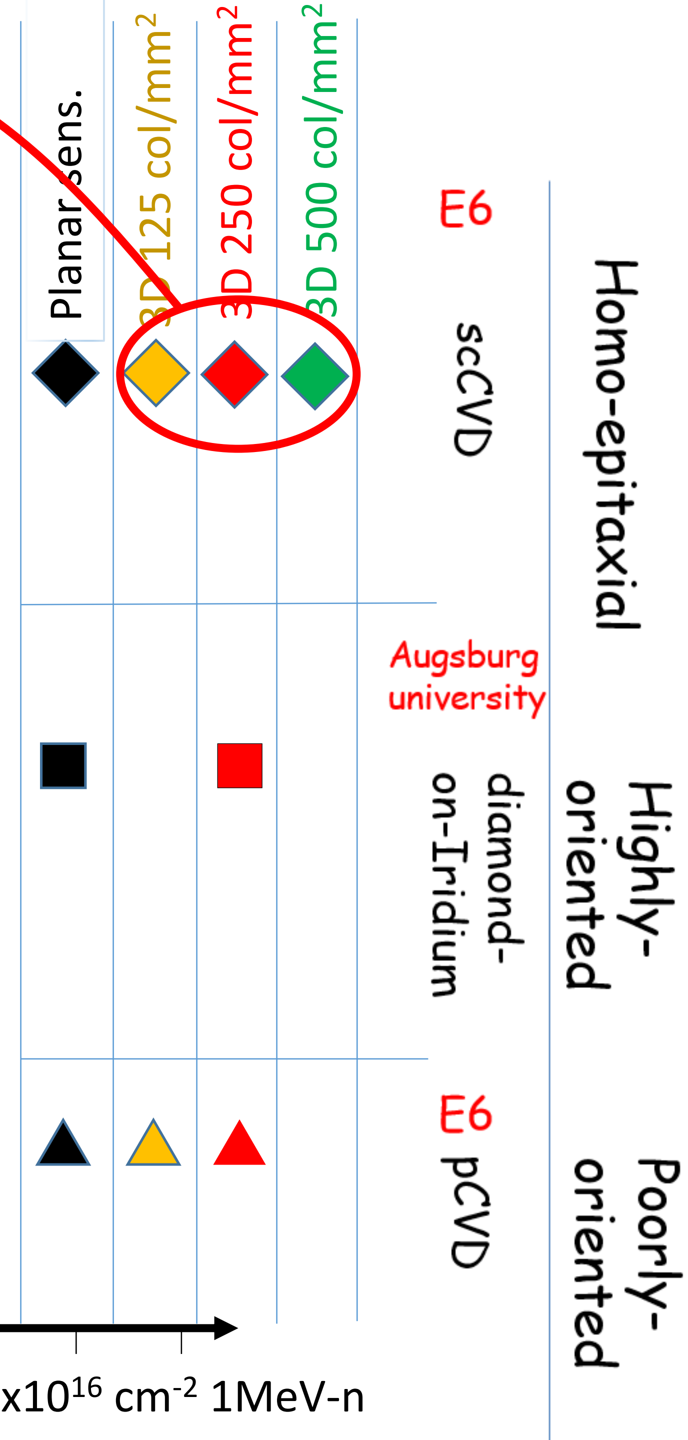


A preliminary question:

The 3D sensors in SC diamond were fabricated with the same parameters:

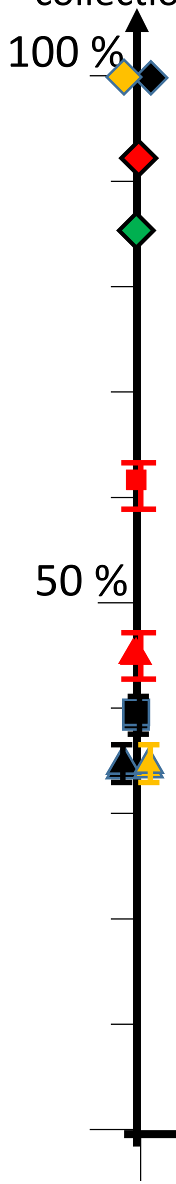
1) The same diamond plate
2) Pulse duration
3) Pulse energy
4) Repetition rate
5) Translation velocity

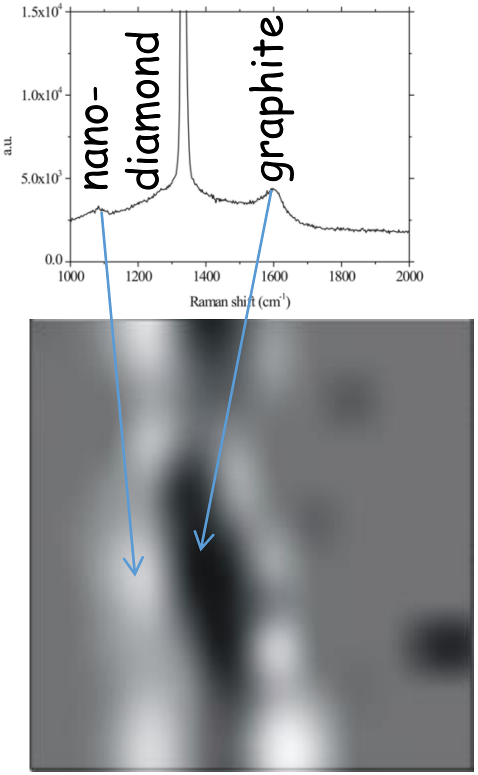
Nevertheless:
Higher column densities→lower efficiency… Why?

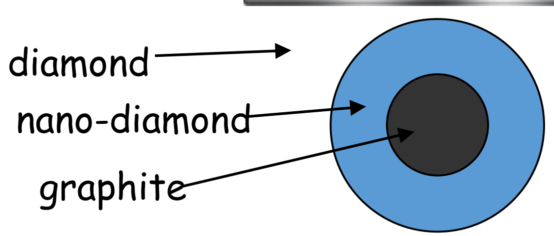


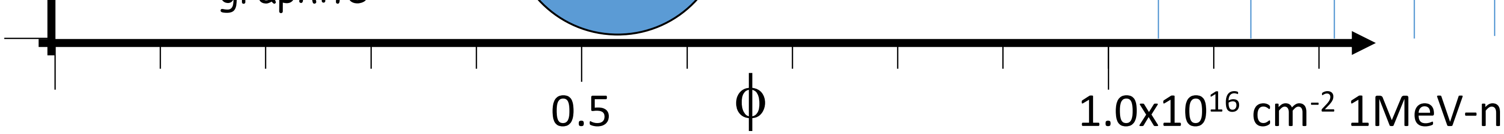
*Applied Physics Letters 103 (2013) 233507

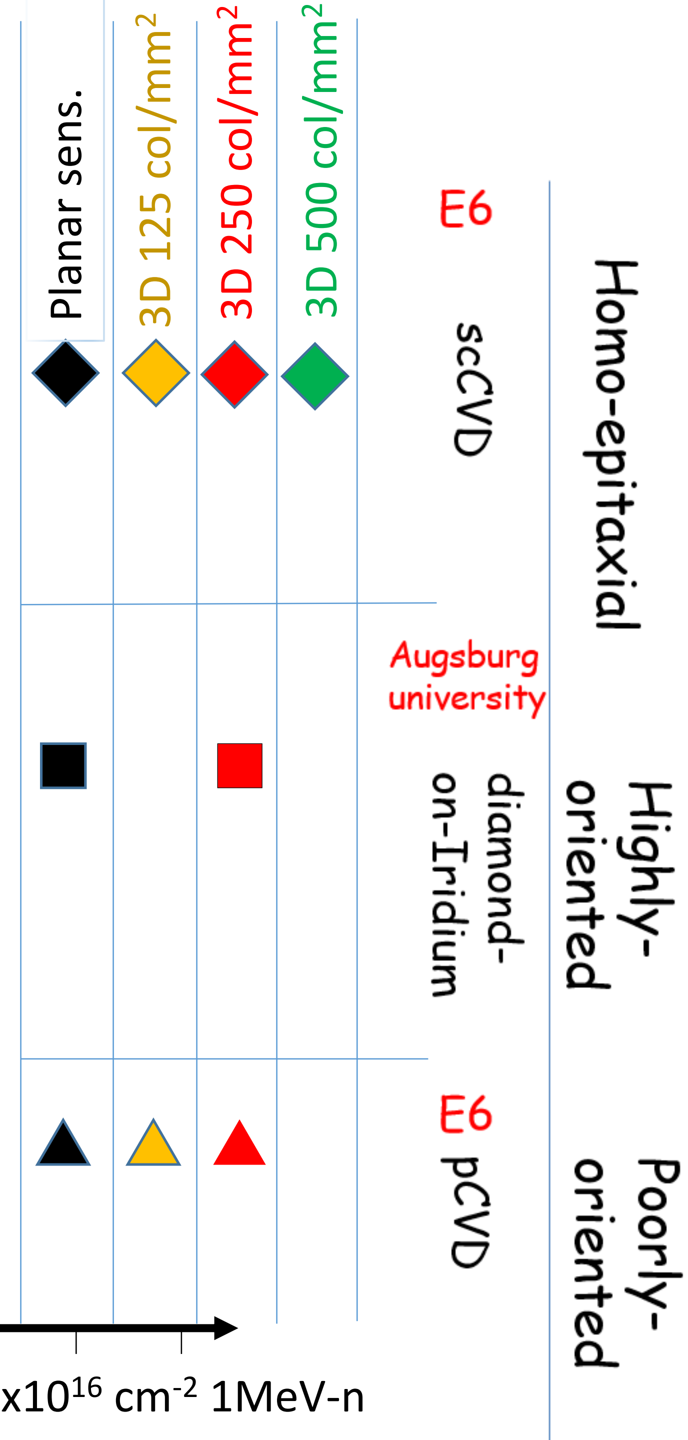
We have verified in the past* that possible lower efficiency in 3D sensors are correlated with a nano-diamond layer surrounding the graphitic columns:

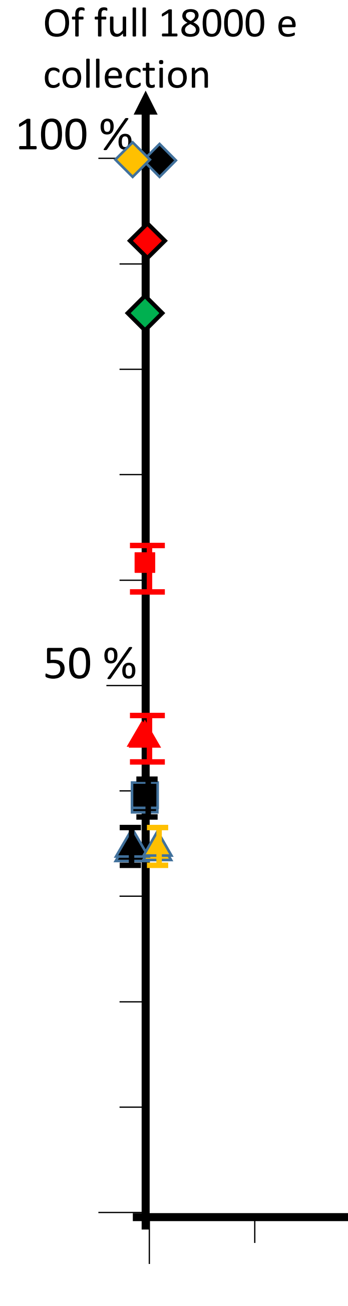




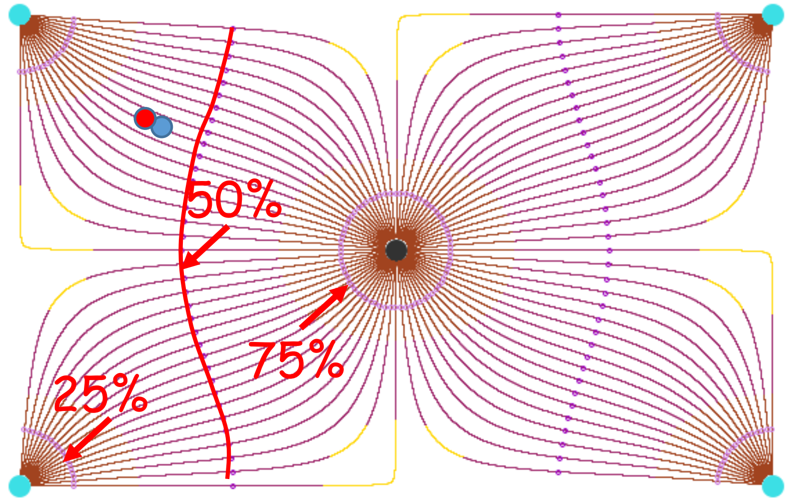






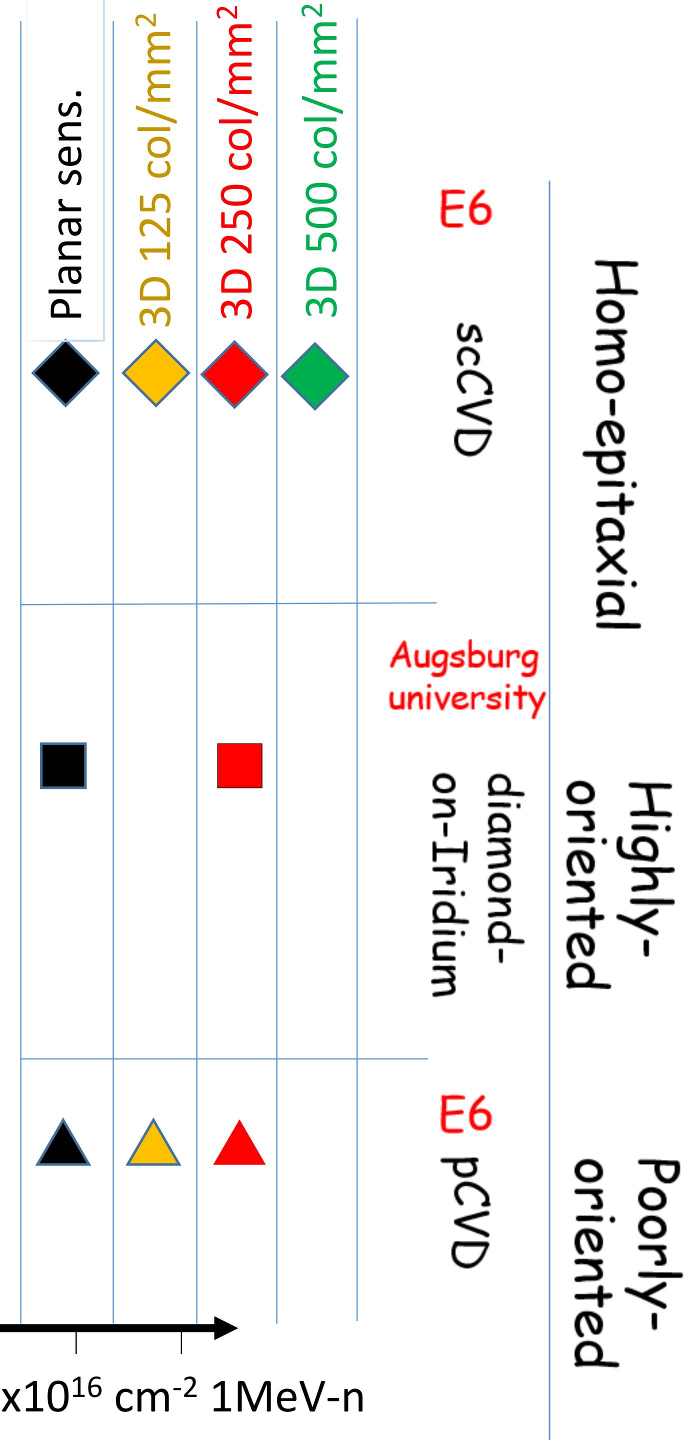


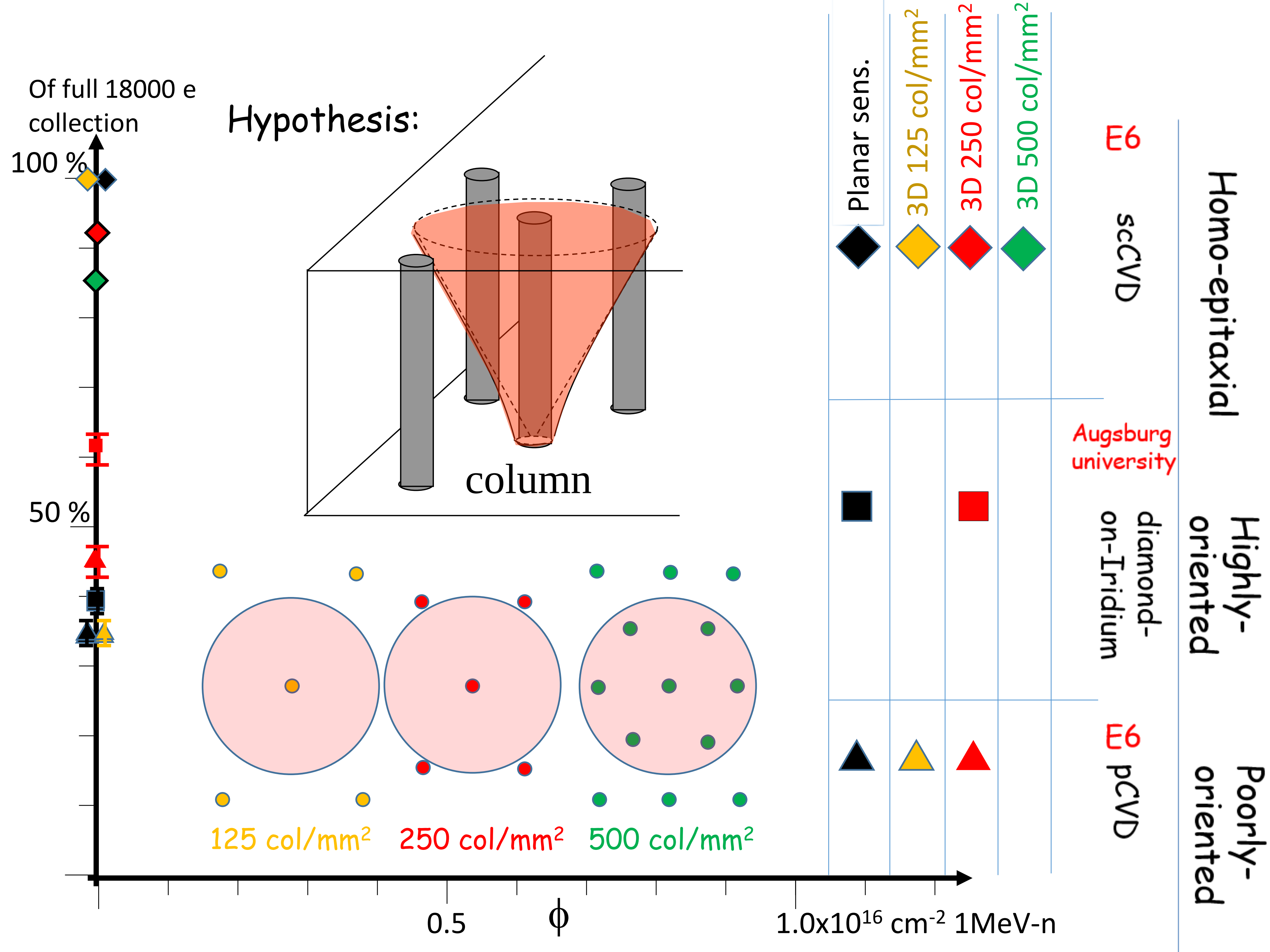
Ramo theorem: Induced charge is proportional to the voltage drop experimented by the carriers during the motion



Thus, if the carriers are stopped before reaching conductive columns, a sensible efficiency drop can be determined even if the defective layer is quite thin (5 μm)

Now: why a higher column density shoud determine a defective layer around columns?



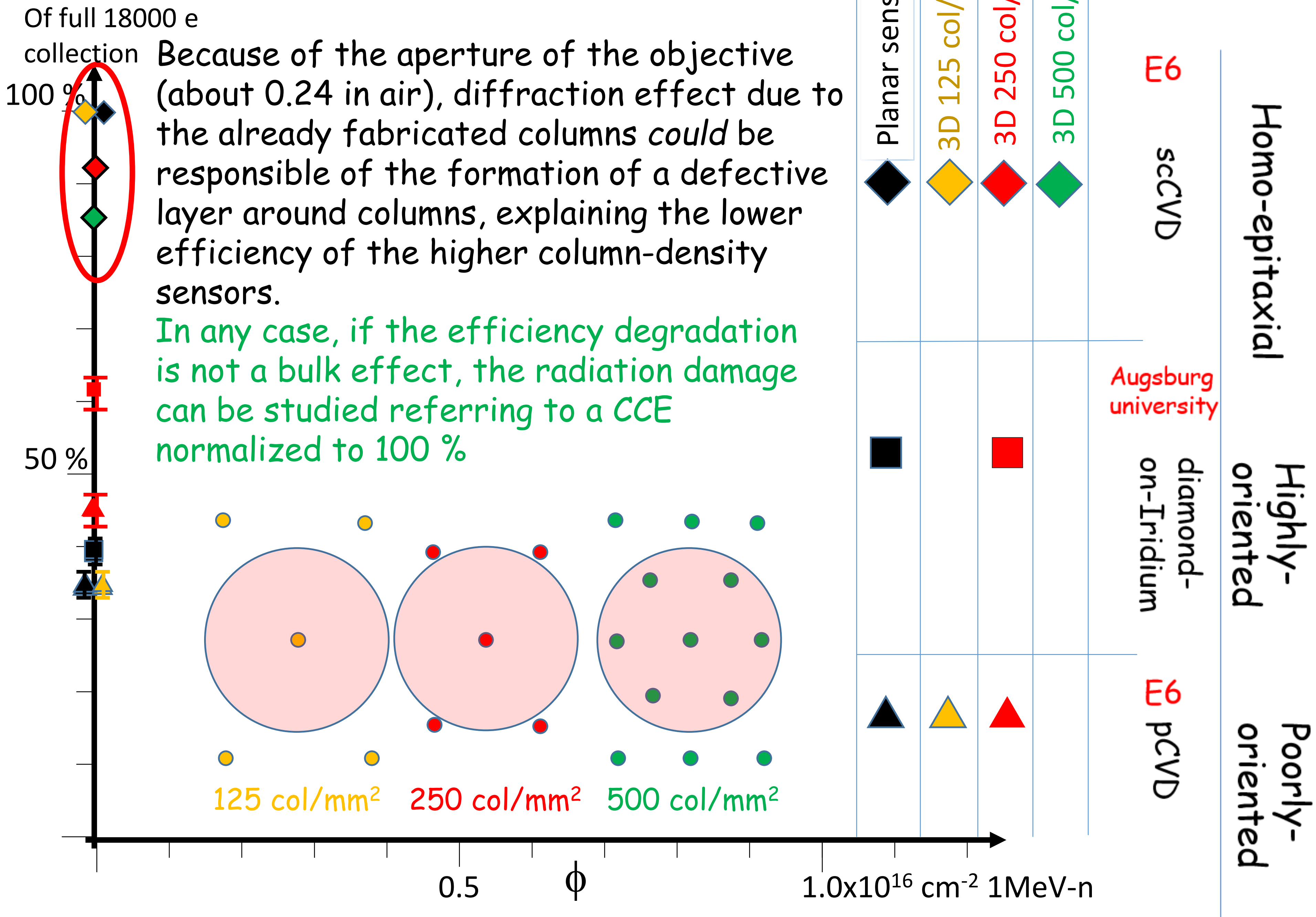


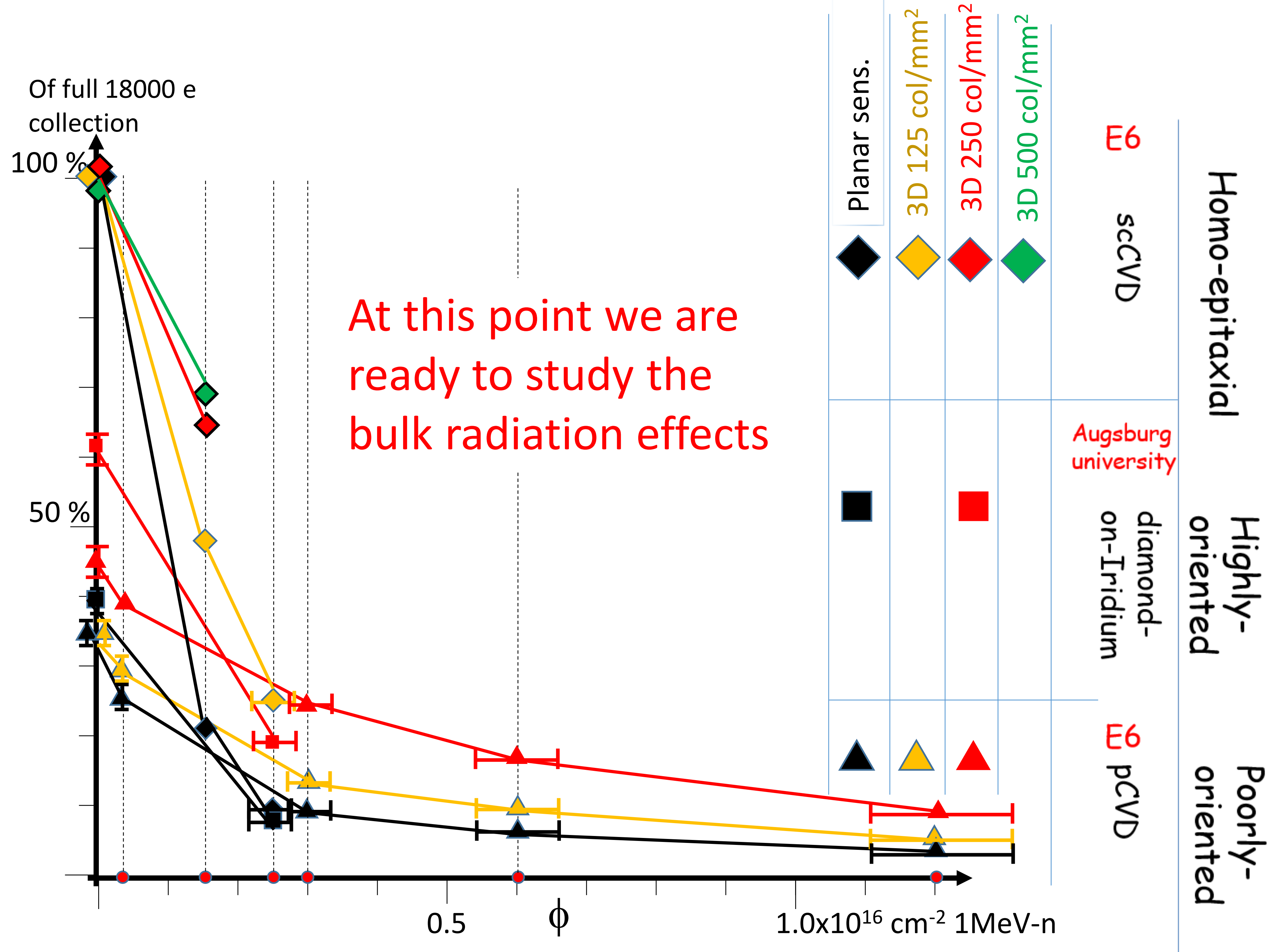
Of full 18000 e collection
100 %
50 %
Hypothesis:
column
125 col/mm²
250 col/mm²
500 col/mm²
0.5
ϕ
1.0x10¹⁶ cm⁻² 1MeV-n
Planar sens.
3D 125 col/mm²
3D 250 col/mm²
3D 500 col/mm²
E6
scCVD
Homo-epitaxial
Augsburg university
diamond-on-Iridium
Highly-oriented
E6
pCVD
Poorly-oriented

Hypothesis:

Because of the aperture of the objective (about 0.24 in air), diffraction effect due to the already fabricated columns *could* be responsible of the formation of a defective layer around columns, explaining the lower efficiency of the higher column-density sensors.

In any case, if the efficiency degradation is not a bulk effect, the radiation damage can be studied referring to a CCE normalized to 100 %





Of full 18000 e collection
100 %
50 %
0.5
ϕ
1.0x10^16 cm^-2 1MeV-n
At this point we are ready to study the bulk radiation effects
Planar sens.
3D 125 col/mm²
3D 250 col/mm²
3D 500 col/mm²
E6
scCVD
Homo-epitaxial
Augsburg university
diamond-on-Iridium
Highly-oriented
E6
pCVD
Poorly-oriented

CCE Simulation

Basic hypothesis:

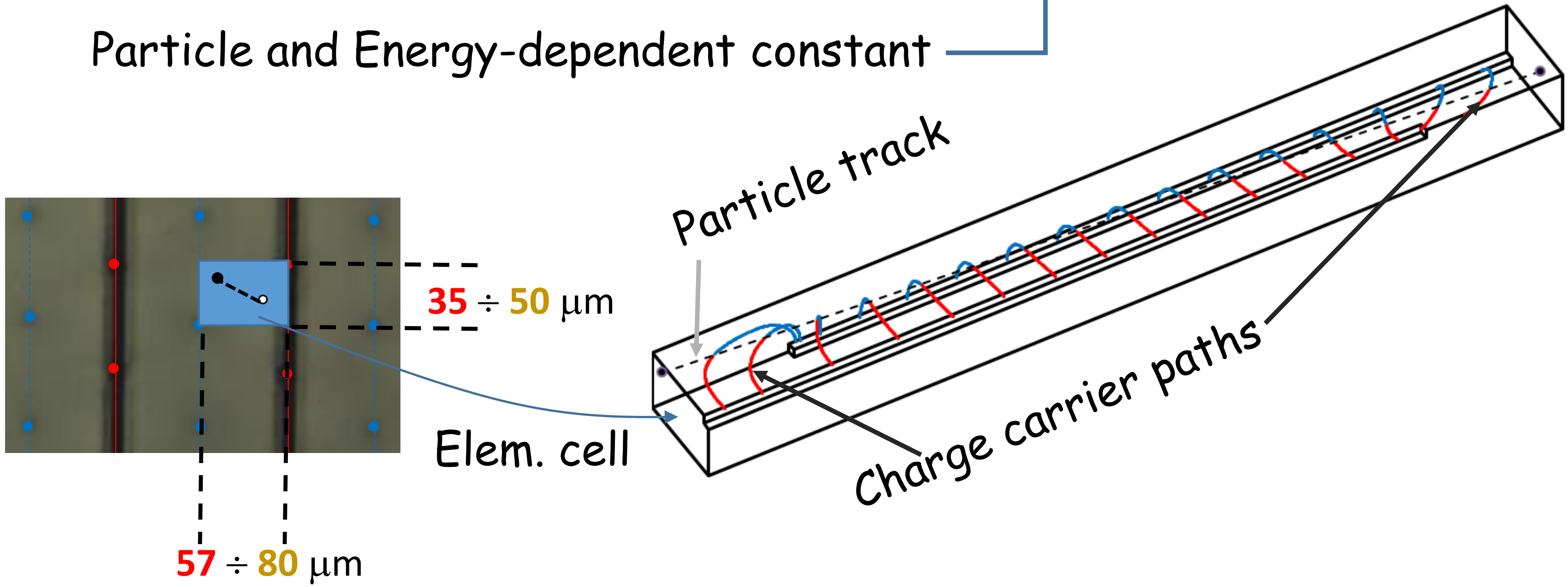
$$\frac{1}{\tau} = \frac{1}{\tau_0} + k\Phi$$

Trapping probability

Trapping prob. at 0 fluence

Particle and Energy-dependent constant

Particle fluence



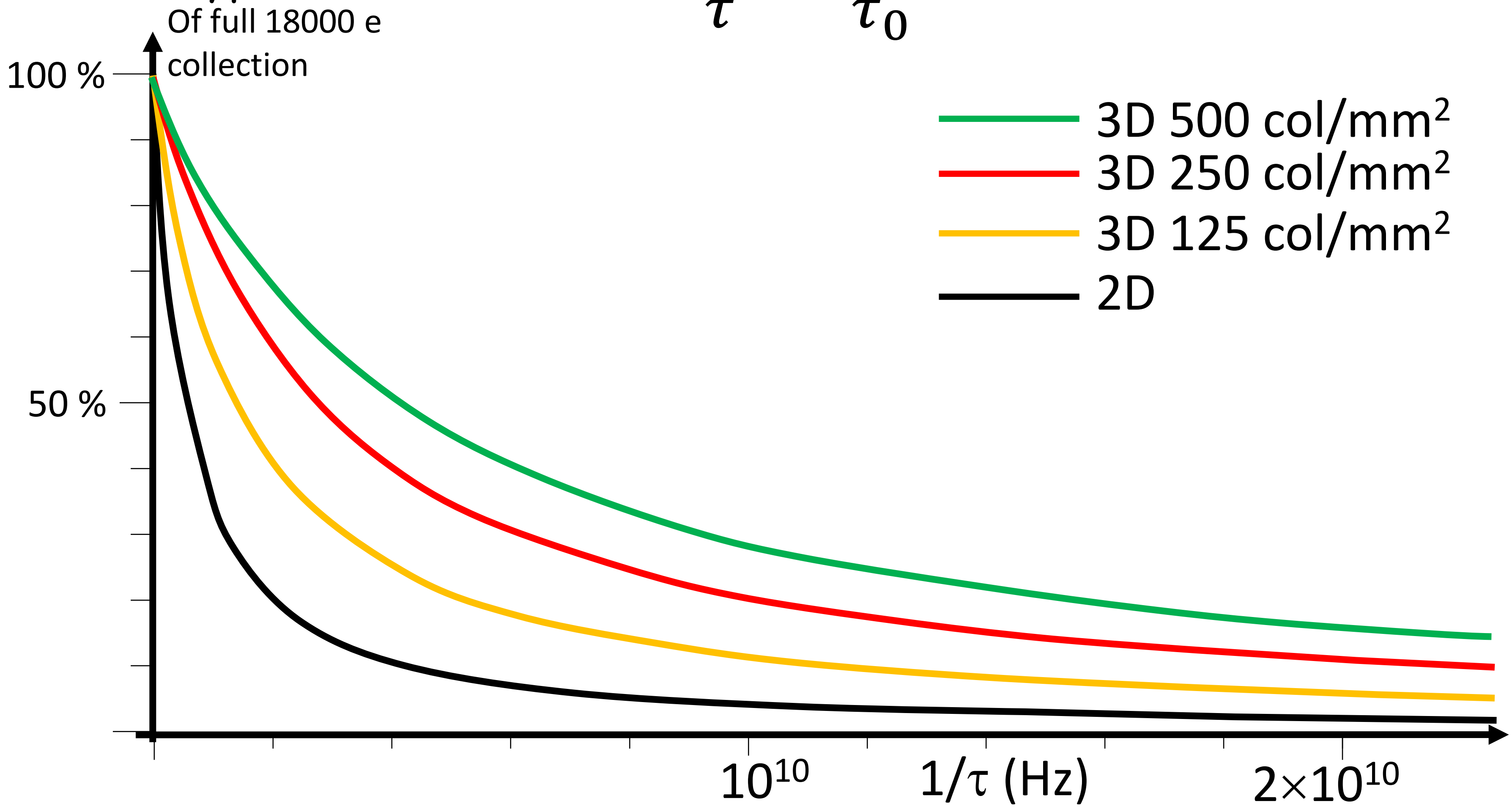
Random particle tracks → Monte Carlo simulation of the charge collection efficiency, given

Electrodes geometry:	2D	3D 125 col/mm²	3D 250 col/mm²	3D 500 col/mm²
Trapping probability:		$0 < 1/\tau < 2.2\times10^{10}$ Hz		
Bias voltage:	600 V	70 V	70 V	70V

CCE Simulation

Basic hypothesis:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + k\Phi$$



Random particle tracks → Monte Carlo simulation of the charge collection efficiency, given

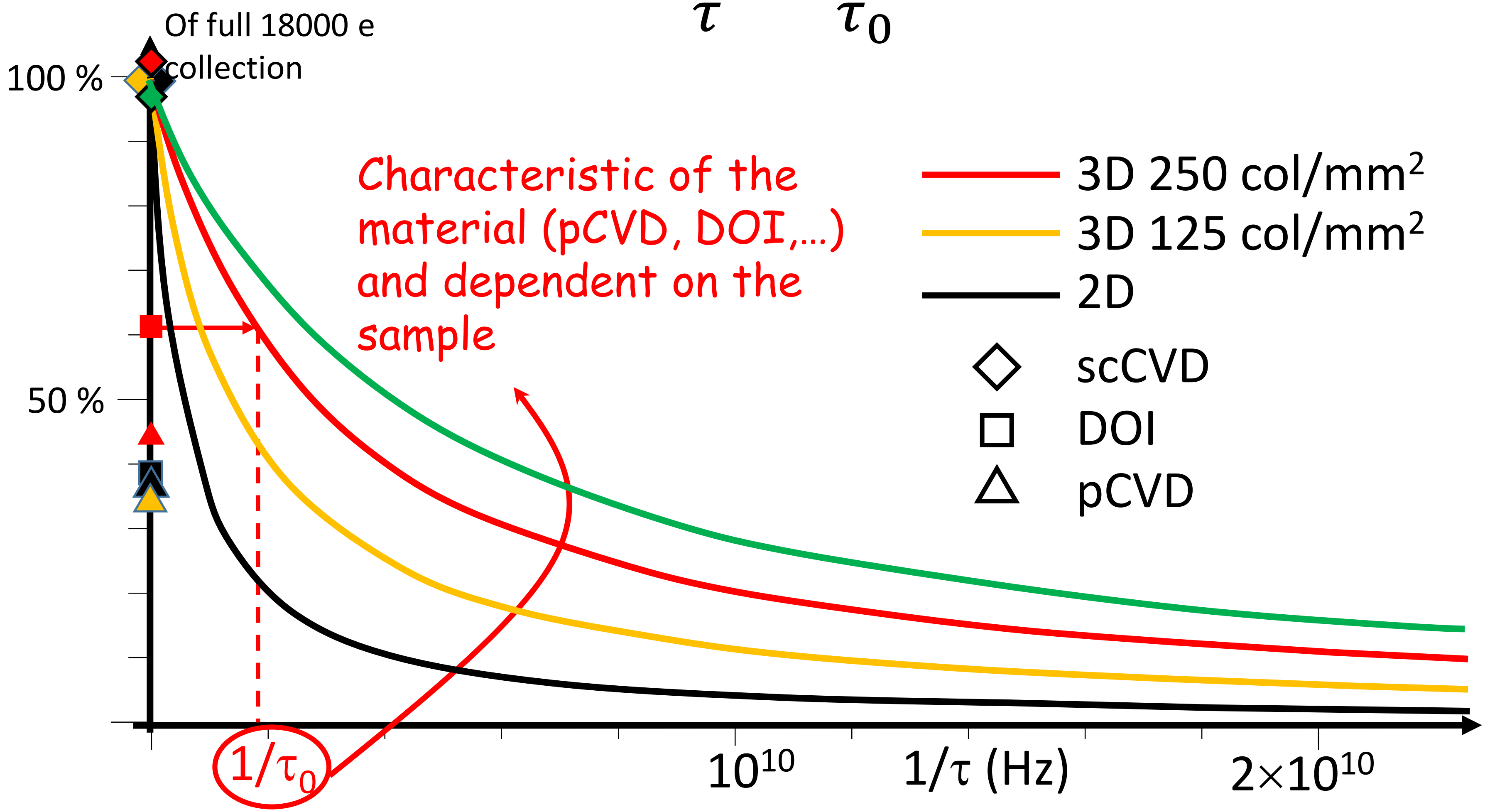
Electrodes geometry: 2D 3D 125 col/mm^2 3D 250 col/mm^2 3D 500 col/mm^2

Trapping probability: $0 < 1/\tau < 2.2\text{x}10^{10}$ Hz

Bias voltage: 600 V 70 V 70 V 70V

Basic hypothesis:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + k\Phi$$

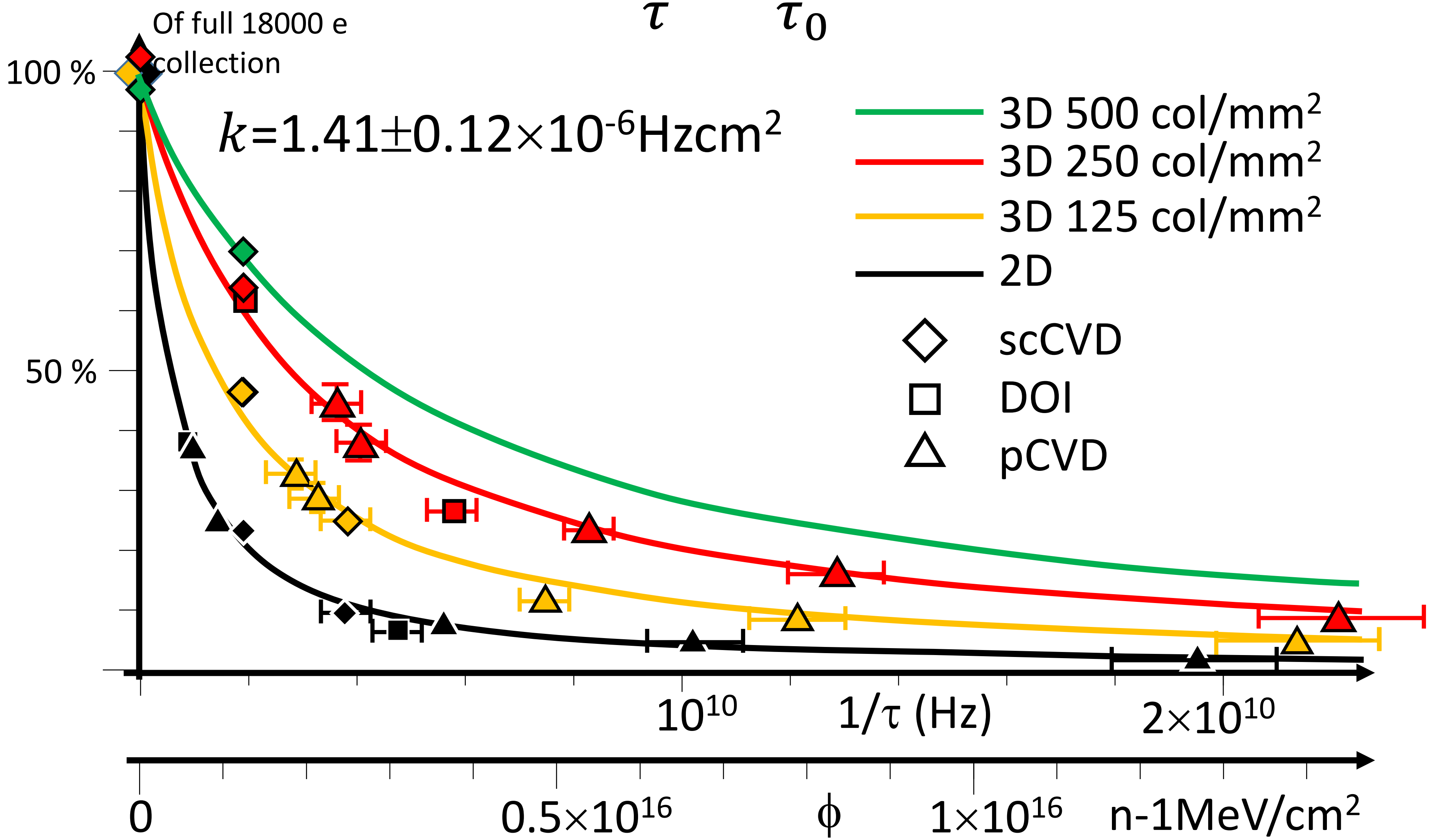


For each sensor, at ϕ=0, the CCE is determined by a different value of $1/\tau_0$,

Thus, with a suitable choice of the constant *k* (that is: the scale of the fluences) all the other experimental points lies on the correspondent curve

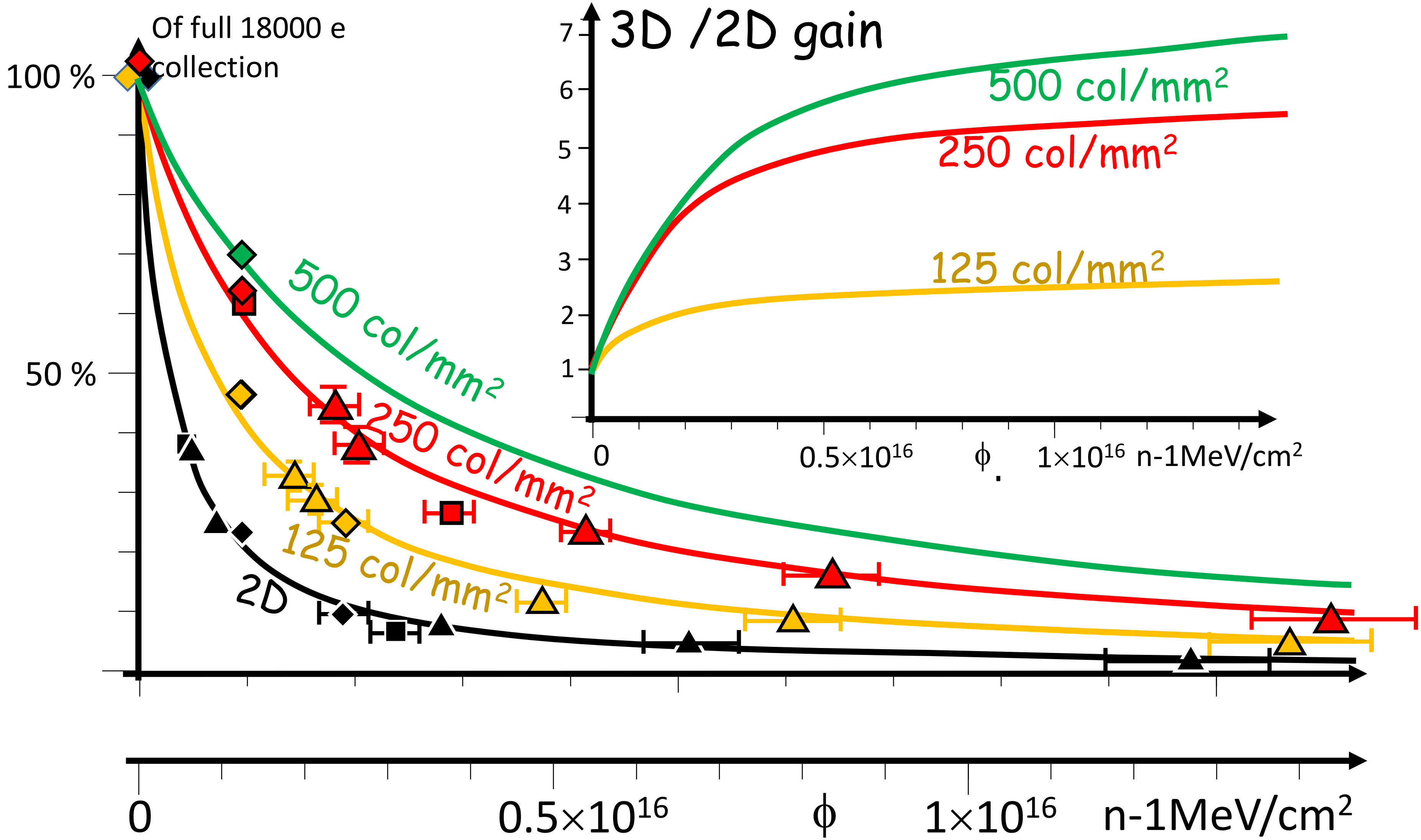
Basic hypothesis:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + k\Phi$$



Thus, with a suitable choice of the constant k (that is: the scale of the fluences) all the other experimental points lies on the correspondent curve

Conclusions and perspectives:



The 3D / 2D gain reaches a factor 5.5 for the 250 col/mm² sensors!

With a 500 col/mm² sensors, it could reach a factor 7

Conclusions and perspectives:

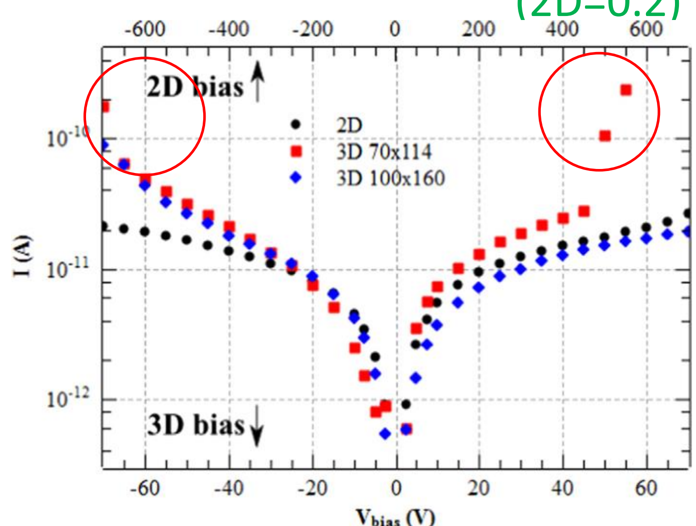
125	250	500 col/mm²
2.5	5.5	7 damaged 3D/2D CCE
100%	~91%	~83% undamaged CCE
1.25%	2.5%	5% dead vol.
1.5	3	6 pf/mm² (2D=0.2)

1) With our technology, the initial CCE is slightly lower than 100% for the higher column densities.

2) Each column has a cross-section of about 100 μm^2, which limits the detector volume

3) Capacity/unit-surface increases with column density, which increases the noise level

4) run-away currents tend to appear at high voltages, more pronounced with shorter inter-electrode distances



Conclusions and perspectives:

There is probably a value around 180-200 col/mm^2 with:
- 3D/2D gain = 3 ÷ 4
- 100% CCE at 0 fluence
- <2% dead volume

The performances of single and poly-crystalline diamond sensors, in term of collected charge after strong radiation damage, could be improved by implementation of the 3D concept of at least a factor 3, compared with conventional planar detectors, with limited (<2%) lost of active volume and tolerable increase of capacity (~2 pf/mm^2).

Further readings

Photoionization of monocrystalline CVD diamond irradiated with ultra-short intense laser pulses S Lagomarsino, S. Sciortino, B. Obreskov, T. Apostolova, C. Corsi, M. Bellini, E. Berdermann, C. J. Schmidt. Submitted to Physical Review B (2015)

Radiation hardness of three-dimensional polycrystalline diamond detectors S Lagomarsino, M Bellini, C Corsi, V Cindro, K Kanxheri, A Morozzi, D Passeri, L Servoli, C J Schmidt and S Sciortino Applied Physics Letters 106 (2015) 193509

Polycrystalline diamond detectors with three-dimensional electrodes S Lagomarsino, M Bellini, M Brianzi, R Carzino, V Cindro, C Corsi, A Morozzi, D Passeri, S Sciortino, L Servoli Nuclear Instruments and Methods in Physics Research Section A 796 (2015) 42

Electrical and Raman-imaging characterization of laser-made electrodes for 3D diamond detectors S Lagomarsino, M Bellini, C Corsi, S Fanetti, F Gorelli, I Liontos, G Parrini, M Santoro, S. Sciortino Diamond and Related Materials 43 (2014) 23-28

Three-dimensional diamond detectors: Charge collection efficiency of graphitic electrodes S Lagomarsino, M Bellini, C Corsi, F Gorelli, G Parrini, M Santoro, S Sciortino Applied Physics Letters 103 (2013) 233507

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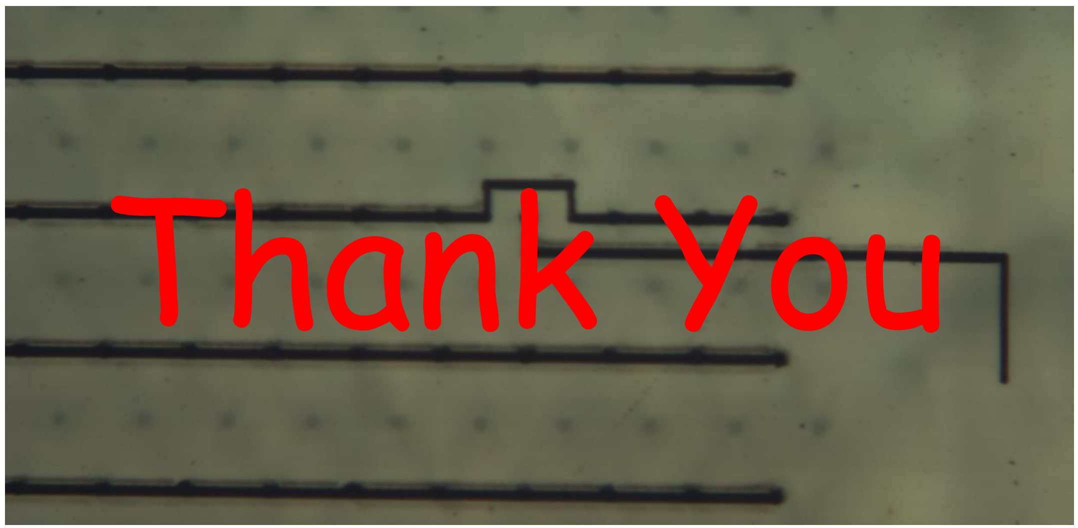
Advances in 3D diamond detectors fabrication and tests in Florence



S.Lagomarsino[1,2], T. Apostolova[3], M. Bellini[4], V. Cindro[5], C. Corsi[1,6], K. Kanxheri[7,8], A. Morozzi[7,8], B. Obreskov[3], D. Passeri[7,8], L. Servoli[8], E. Berdermann[9], M. Kis[9], M.Fischer[9], C. J. Schmidt[9], M. Träger[9], R. Visinka[9], M.Schreck[10], S.Gsell[10], and S. Sciortino[1,2]

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