Space Passive Component Days, 1st International Symposium
24-26 September 2013. ESA/ESTEC, Noordwijk, The Netherlands

High Power and Energy Density Ultracapacitor For Space Environment

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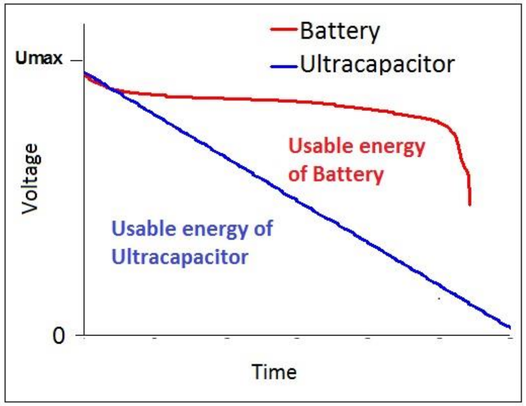
What is an Ultracapacitor?

Ultracapacitor or ***Supercapacitor*** or ***Electrochemical capacitor***.

- Electrochemical energy storage device having higher energy density than dielectric capacitors and higher power density than batteries.
- Consists of two high-surface electrodes separated by a porous membrane immersed in an electrolyte.
- Electrochemical energy storage device in which the voltage declines linearly with the extent of charge.



<u>EDLC</u>

electrostatic
energy storage

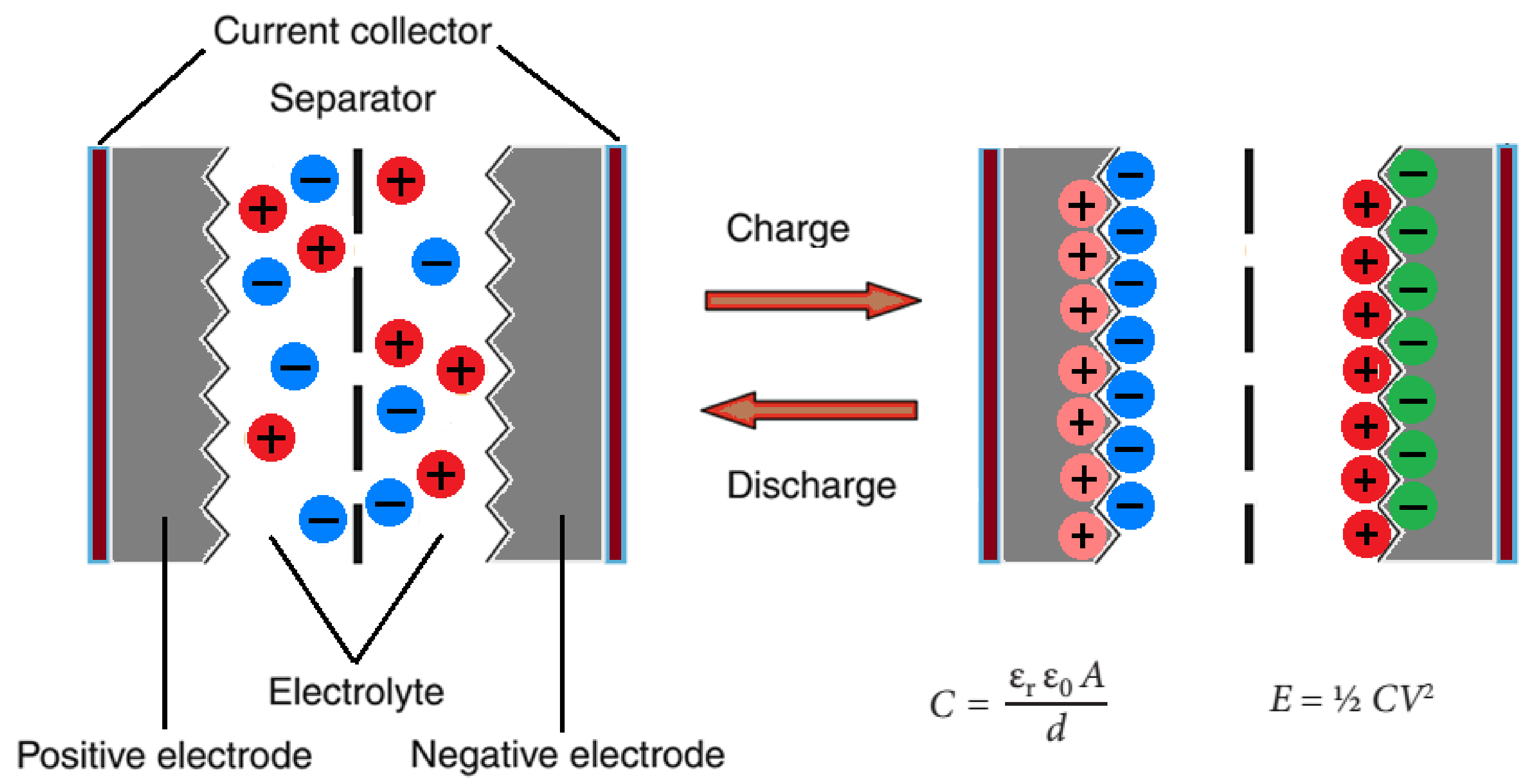
<u>Pseudocapacitor</u>

red-ox
energy storage

<u>Hybrid capacitor</u>

red-ox + electrostatic
energy storage

How does it work?



$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

$$E = \tfrac{1}{2} C V^2$$

Why Ultracapacitor ?

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- long cycle life under multiple charge/discharge cycles;
- ability to operate high power demanding payloads within lower mass and volume;
- high charge/discharge efficiency;
- easily measurable State of Charge (SoC), improving power distribution management;
- less sensitive to temperature, therefore simpler thermal system and lower mass;
- high power that is possible to obtain for low temperatures.

Conventional ultracapacitors

Conventional ultracapacitors have symmetric design:
two high-surface area carbon electrodes are separated by porous membrane

Properties:

•EDLC cell voltage	2.5–2.7V
•Cell capacitance	1–5000F
•Energy density up to	6 Wh/kg and 8 Wh/L
•Max. specific power	~15 kW/kg
•Lifespan up to	1 000 000 cycles

Maxwell

Ioxus

NessCap

Batscap

Nippon Chemi-con

Applications

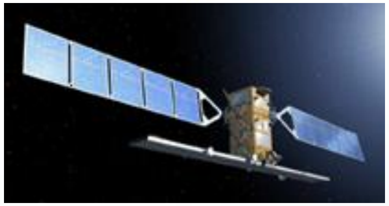
Category	Transport	Power Quality	Renewable energy	Other/ Emerging applications
Benefits	Saving fuel.	Reducing damages from power shortages	Raising the efficiency of energy generation	Saving energy and enhancing performance
Applications	Mass transit; Hybrid-Electric Vehicles; Train/light rail; Back-up power and peripheral power; Electric two-wheel vehicles.	Uninterrupted Power Supply (UPS); Telecom support; Load leveling; Utility Grid Stability; Back-up power (hospitals etc.); Start-up power for fuel-cells.	Wind mill pitch control; Solar panel positioning; Variable energy; Wave energy; Energy dispatching.	Material handling (lifting power for forklift and scissor lifts); Power tools; Backup power for airbag deployment; Communication transmission; Smart meters.

Ultracapacitor for Space

Ultacapacitor-based power subsystem is best suited for missions, where the payloads, or the other subsystems on board, require high power for short operating times (milliseconds to a few minutes).

- **Collision avoidance**

  In a formation flight frame, emergency collision avoidance within 1h is a necessity. Currently, thrusters need a long prewarming phase before any manoeuvre can take place



- **Synthetic Aperture Radar (SAR) payload**

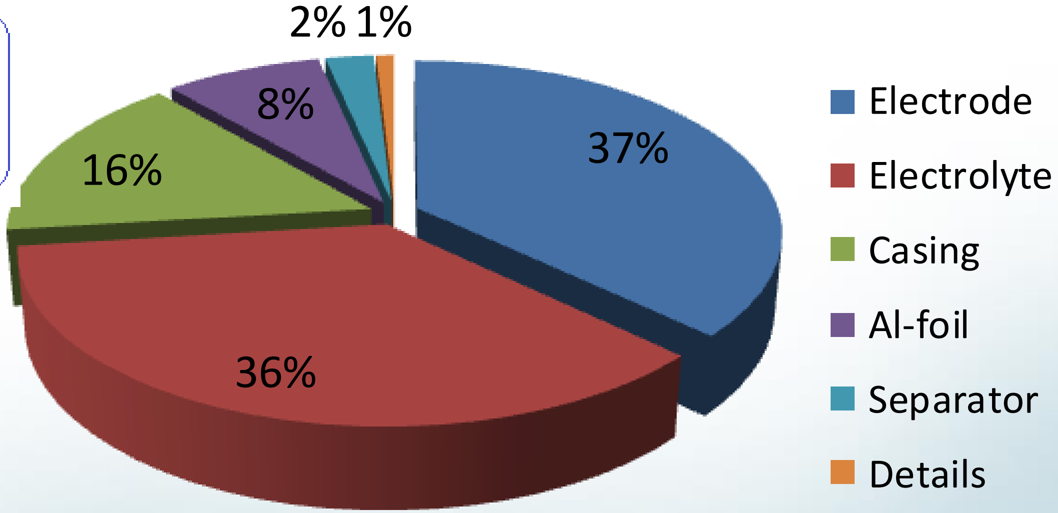
  imaging devices characterised by the emission of narrow high power pulses train

- **Release mechanism**

  Release mechanisms, used to deploy solar panels for example, are triggered after receiving a single pulse signal.

Ultracapacitor structure and components

Electrode: ~90% carbon + ~10% binder
Separator: paper or plastic
Collector: Al-foil



Relative distribution of the ultracapacitor components by weight

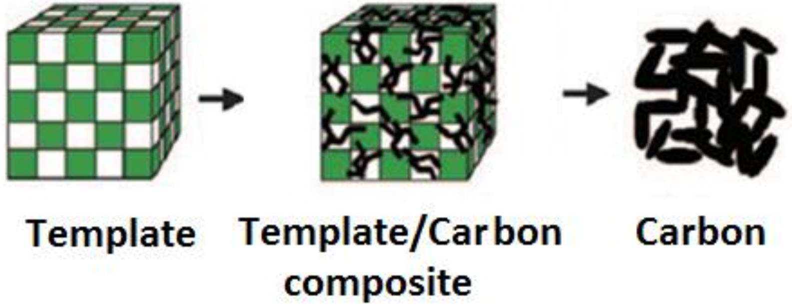
Carbons for Supercapacitor

Activated carbons are known from the first half of the **19th century**, where they were used mostly as adsorbents also in First World War.

Carbon nanotubes discovered by Sumio Iijima of NEC in **1991**, who found these formation as byproduct in fullerene synthesise.

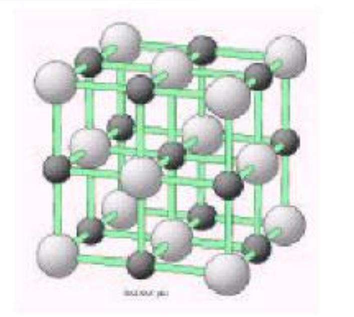
The term **graphene** first appeared in **1987**. A key advance in the science of graphene came when Andre Geim and Kostya Novoselov at Manchester University managed to extract single-atom-thick crystallites (graphene) from bulk graphite in **2004**

Template-made carbons.
Kyotani, 1995

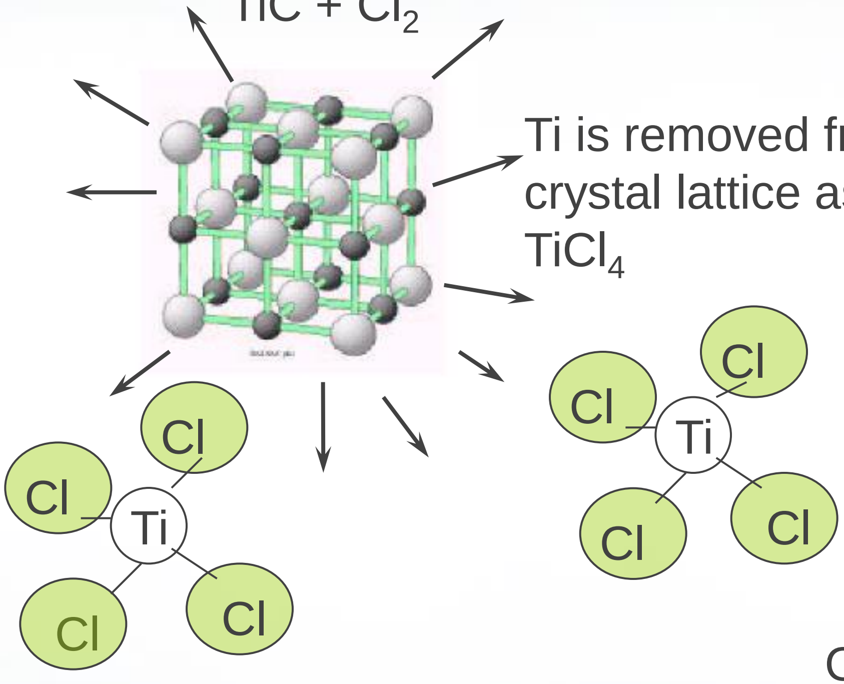


Carbide-Derived Carbon

TiC

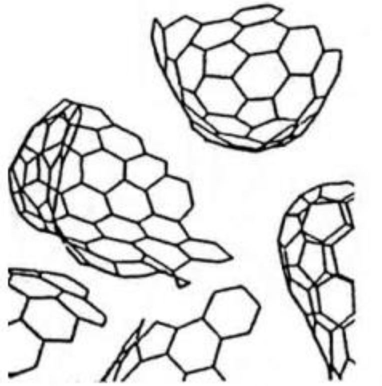


TiC + Cl_2

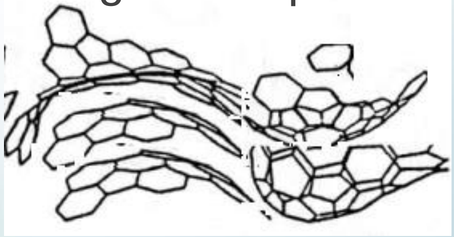


Ti is removed from crystal lattice as $TiCl_4$

Amorphous CDC is formed at lower temperatures



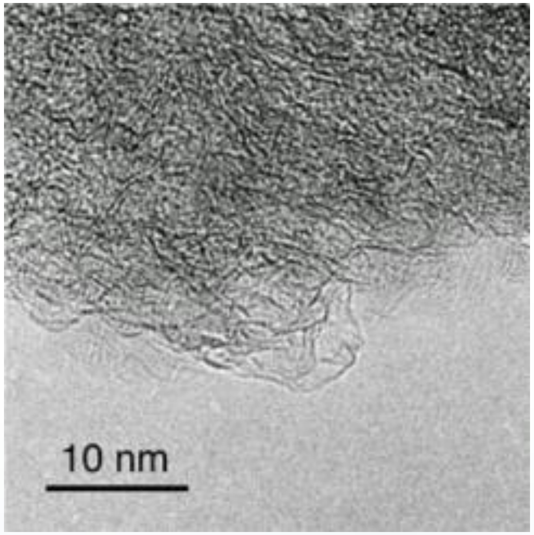
Ordered structures of CDC are formed at higher temperatures



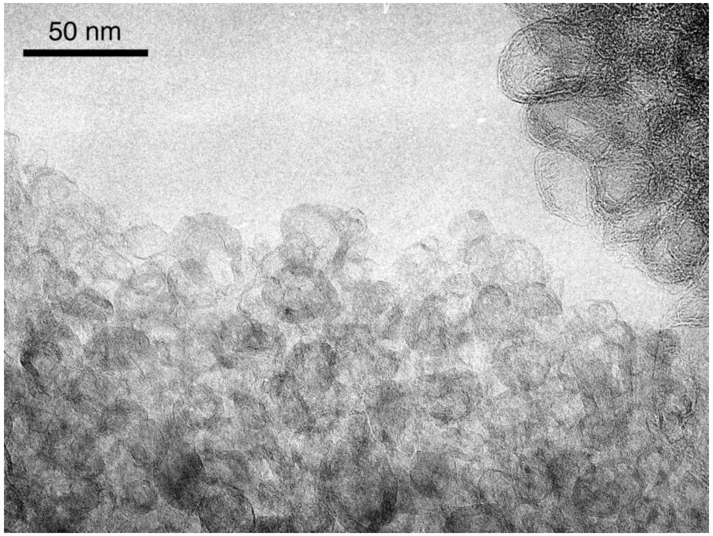
Carbon “remembers” its origin - the carbide.
As simplified, the less carbon is in carbide lattice, the bigger voids would be produced between carbon atoms

HRTEM images of nanostructured CDC

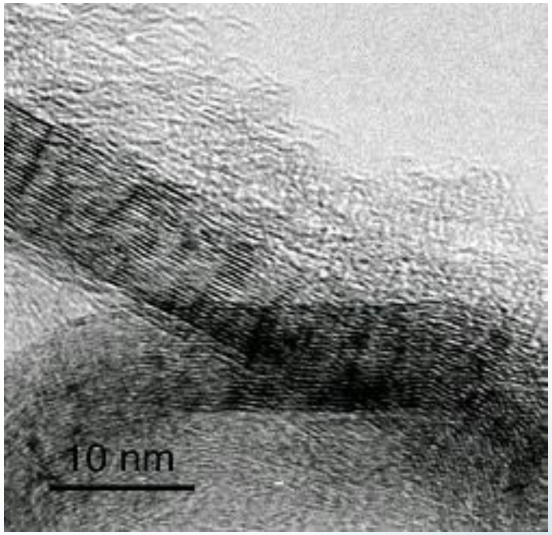
Amorphous microporous



Nanoparticles



Turbostratic



Variable structure: from amorphous to graphite like structures

Pore structure characteristics of variable CDC materials

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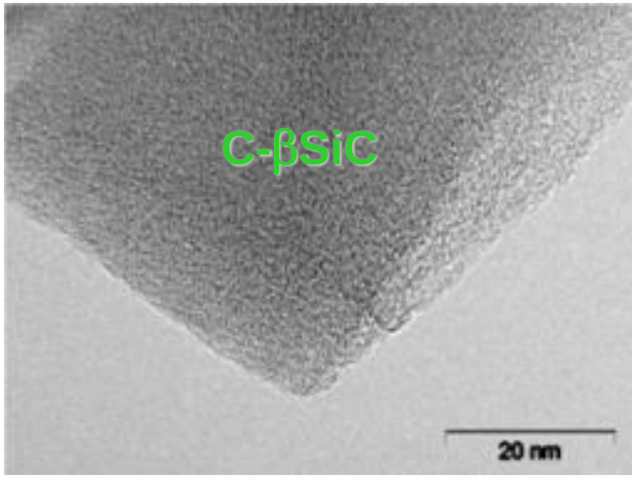
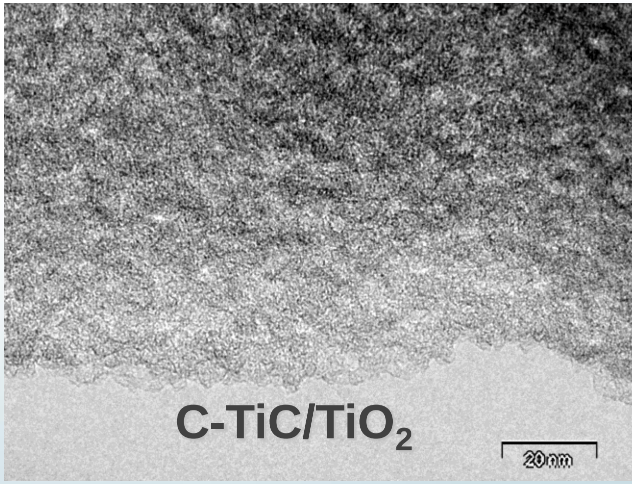
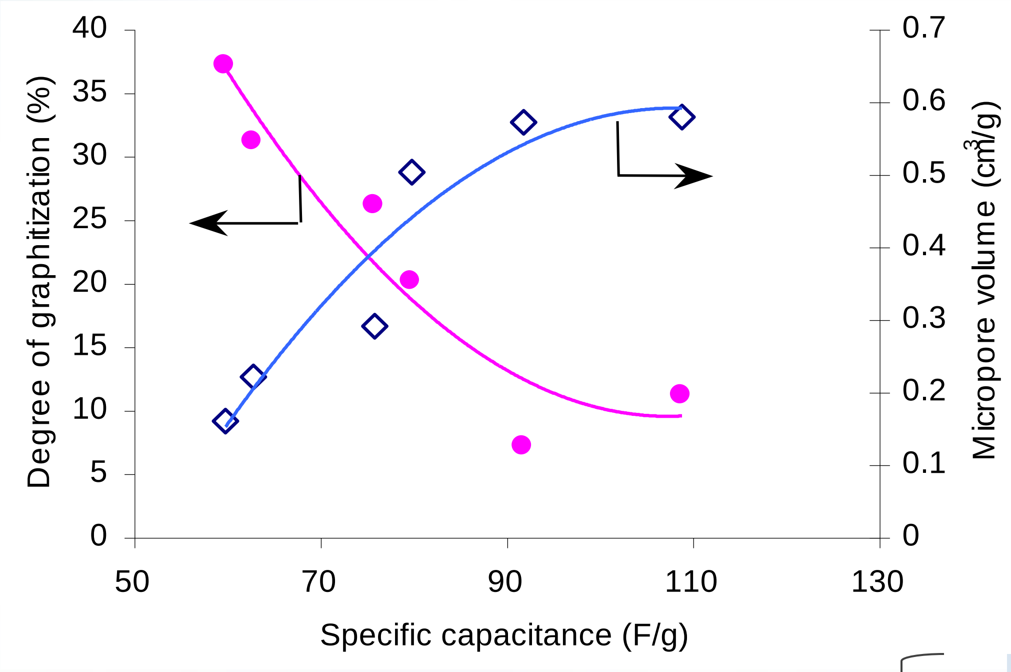
$$MC_x + y/2\ Cl_2 \rightarrow xC + MCl_y$$

	$S_{BET}[m^2g^{-1}]$	Peak pore size [Å]
TiC	1100 – 1500	7 – 9
TiC_x	1300 – 2000	8 – 13
TiC/TiO_2	1300 – 1800	8 – 13
SiC	800 – 1400	7 – 8
Mo_2C	1200 – 2200	8 – 40
B_4C	800 – 1800	9 – 20
Al_4C_3	1100 – 1400	8 – 20
NbC	1200 – 2000	8 – 10
ZrC	1500 – 2000	8 – 10





Best carbon for Ultracapacitor ?



Key characteristics:

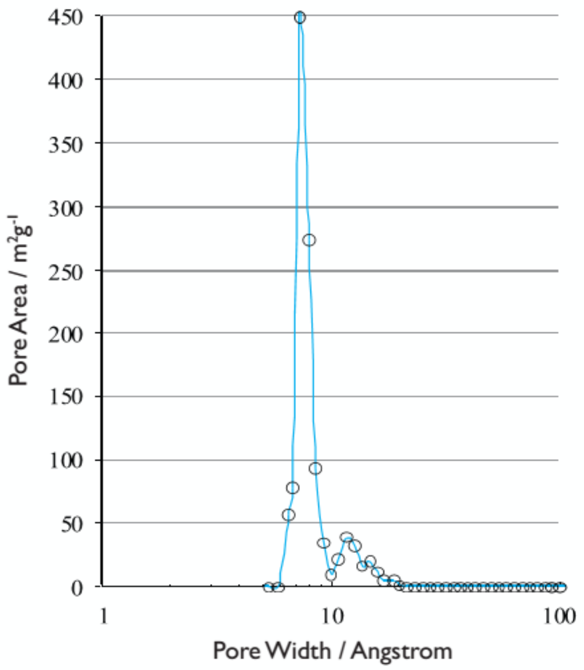
- Electric conductivity
- Surface area
- Pore size distribution
- Packing density
- Cost

CDC is the best !

- Nanoscale fine-tuned nanopore size
- Very high specific surface area
- Adjustable nano- and mesopore content
- Well-defined carbon structure
- High carbon purity

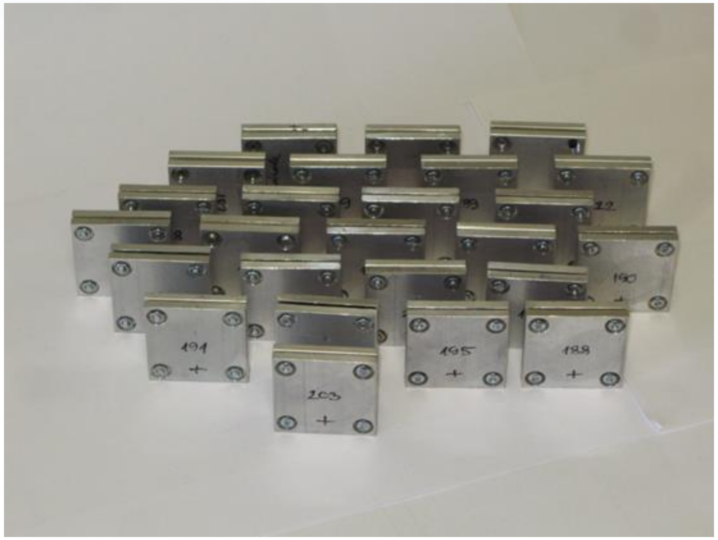
CDC materials for SpaceCap development

CDC	Origin	S_{BET}	V_{total}	V_{micro}
		m^2/g	cm^3/g	cm^3/g
TiC-1	TiC/600	1200	0.56	0.52
TiC-5	TiC/700	1300	0.62	0.57
TiC-2	TiC/800	1400	0.66	0.60
TiC-6	TiC/800+PT	1450	0.68	0.62
TiC-3	TiC/1000-800+PT	1500	0.70	0.62
TiC-4	TiC/1000+PT	1800	1.00	0.61

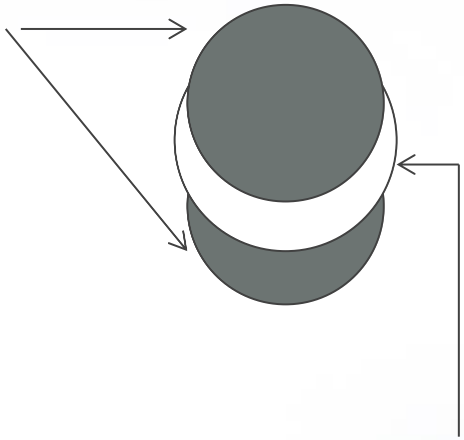


TiC-1

EDLC test-cells



EDLC test-cells for testing components of SpaceCap prototype



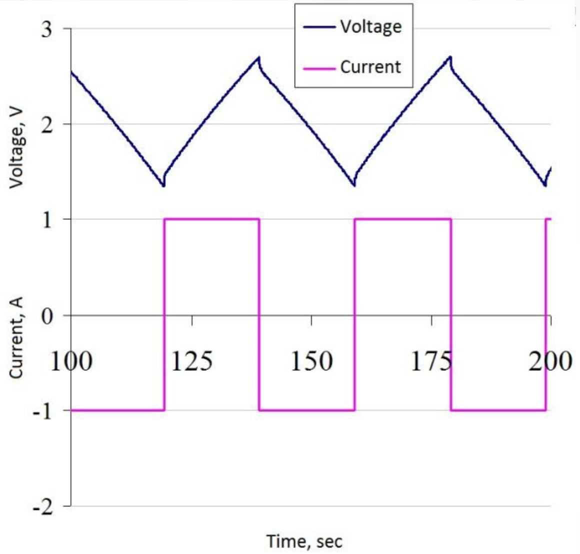
CDC

separator

EDLC test-cells

EDLC #	Anode	Cathode	Separator / Current collector-µm	Electrode thickness [µm]	No. of electrode layers
203	TiC-1	TiC-1	TF4030 / Al-11	60	8+8
221	TiC-1	TiC-1		62	8+8
186	TiC-1	TiC-1		70	7+7
187	TiC-1	TiC-1		90	6+6
188	TiC-1	TiC-1		110	5+5
189	TiC-1	TiC-1		130	4+4
225	TiC-1	TiC-2		140	4+4
191	TiC-3	TiC-4	TF4030 / Al-14	60	8+8
192	TiC-3	TiC-4	Celgard 2500 / Al-11		
211	TiC-3	TiC-4	TF4530 / Al-11		
193	TiC-3	TiC-3	TF4030 / Al-11		
167	TiC-3	TiC-3	TF4030 / Al-11	90	6+6
197	TiC-6	TiC-6			
195	TiC-5	TiC-6			

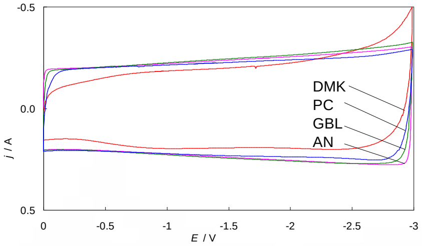
Electrochemical testing procedures



Constant Current Charge-Discharge

(DC-Capacitance, DC-resistance, Energy and Power)

$$C = \frac{I \times \Delta t}{\Delta U} \qquad R = \frac{dV}{dI} \qquad P = I \times \int_{t1}^{t2} U dt \qquad E = P \times (t_2 - t_1)$$



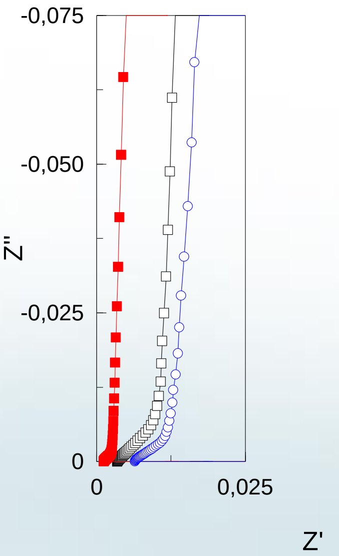
Cycling Voltammetry

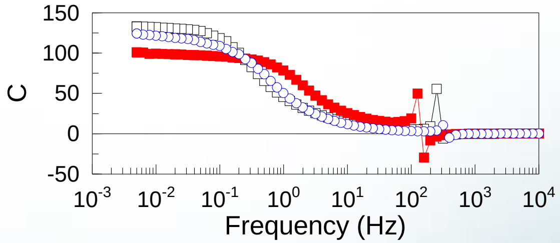
(Capacitance vs. Voltage dependency)

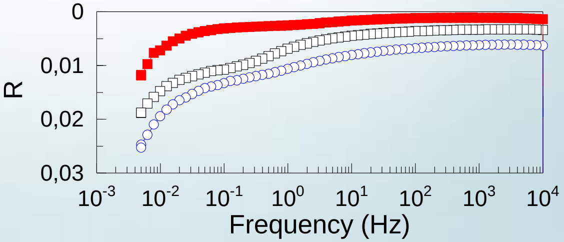
$$C = \frac{I}{v}$$

Electrochemical Impedance Spectroscopy

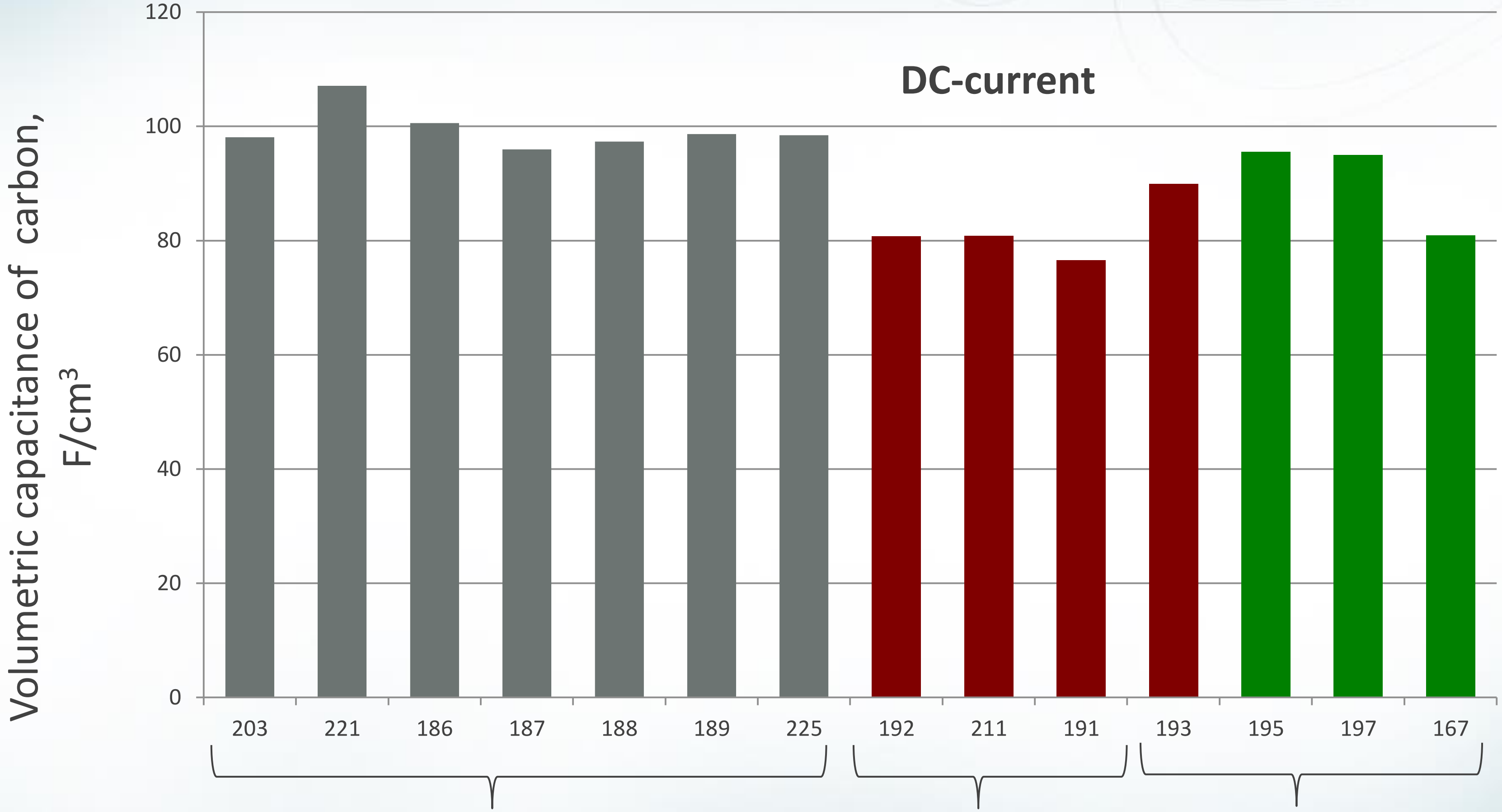
(AC-capacitance vs. Frequency;
AC resistance vs. Frequency and
pore resistance in carbon electrodes,
contact- and , electrolyte resistance,
Phase angle, etc.







Summary - capacitance

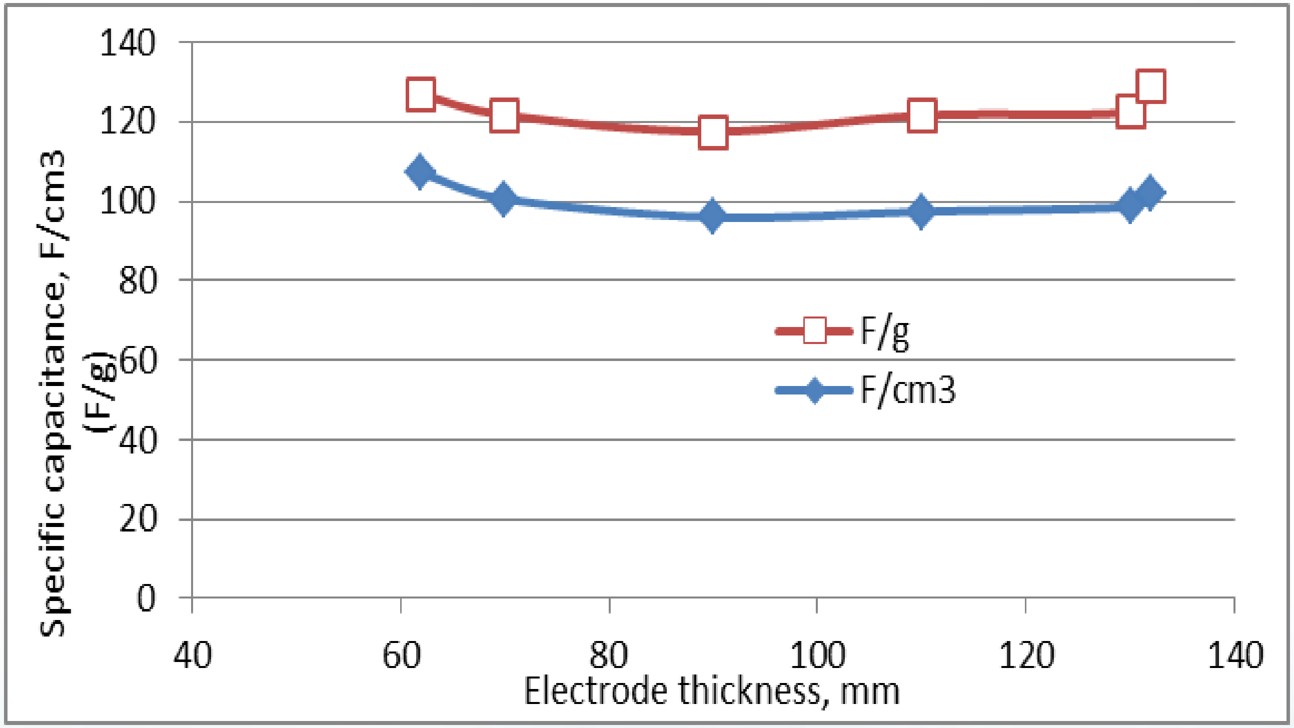


High microporosity

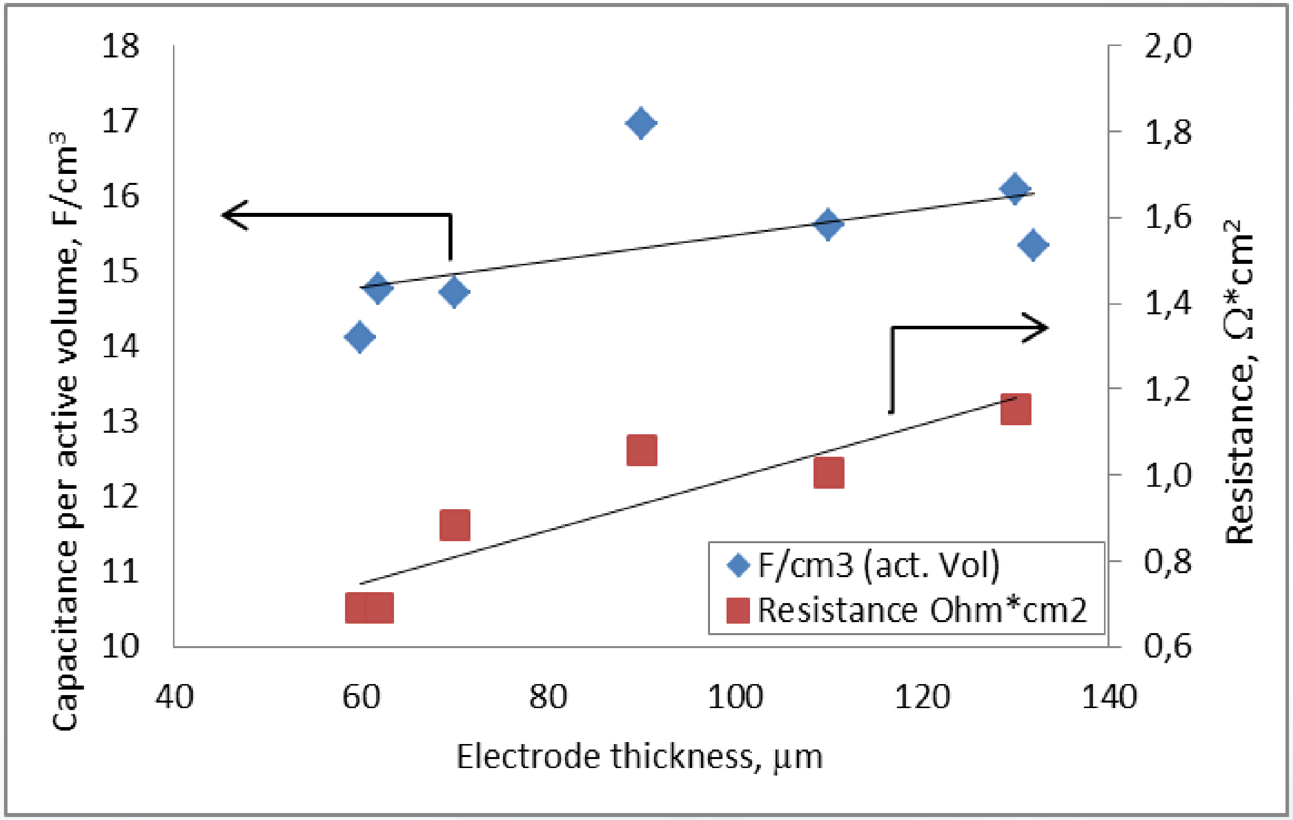
Cathode with increased pore size

Slightly increased micropores

Influence of the electrode thickness



Influence of the electrode thickness



Influence of temperature

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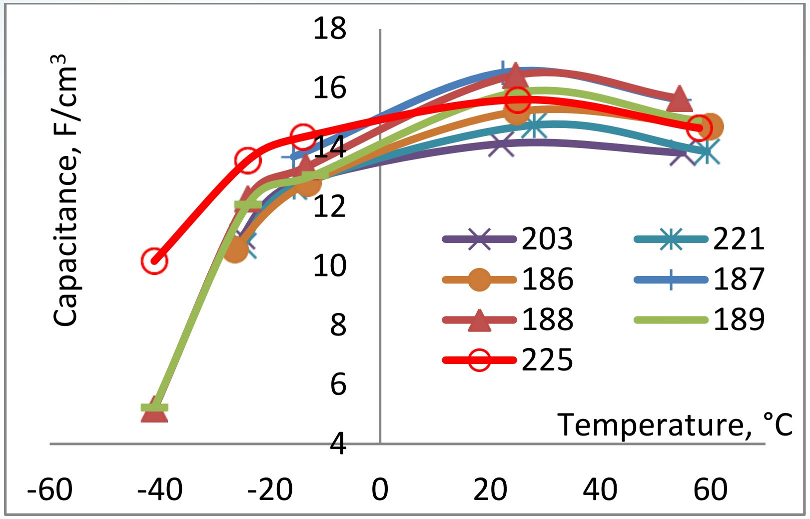

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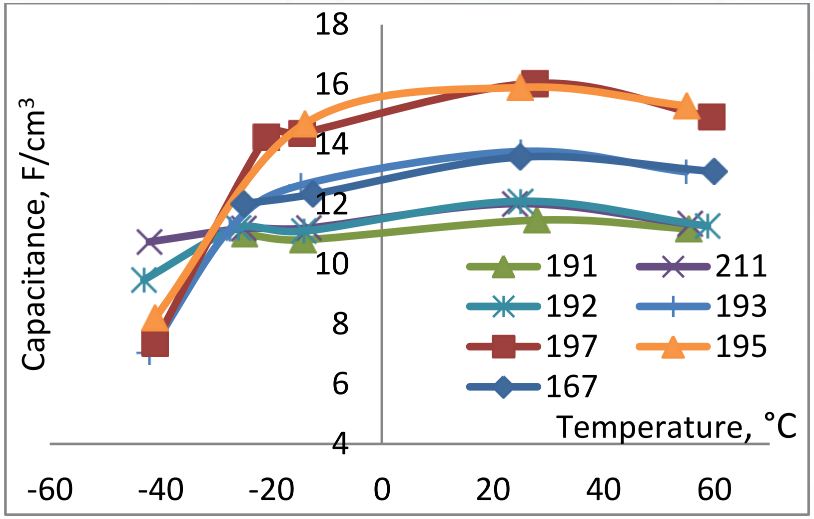

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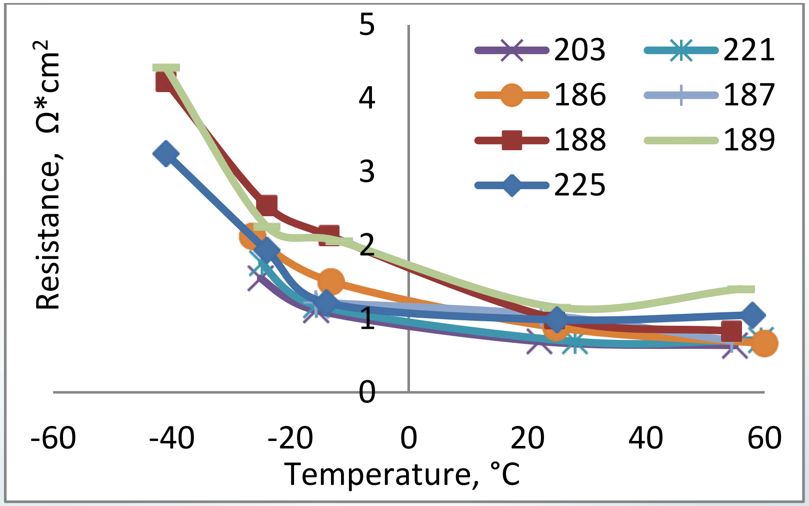

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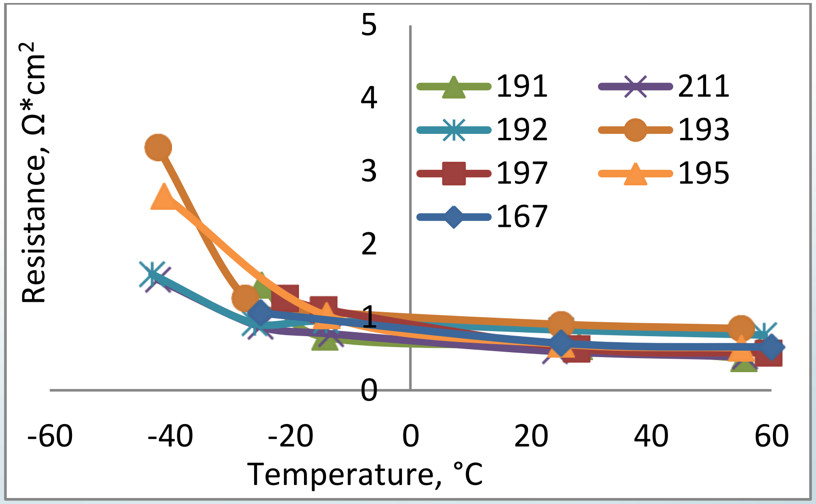

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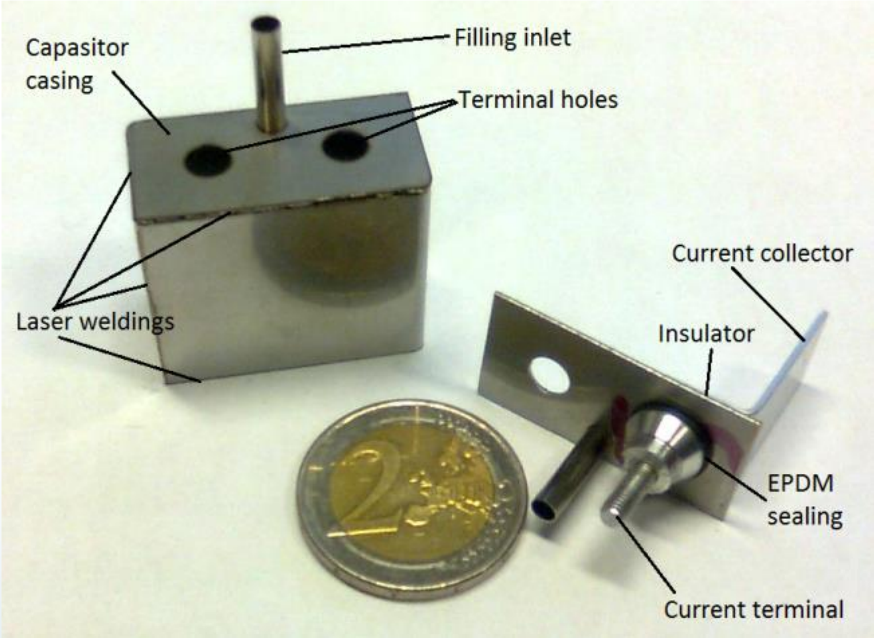
Prototype overview

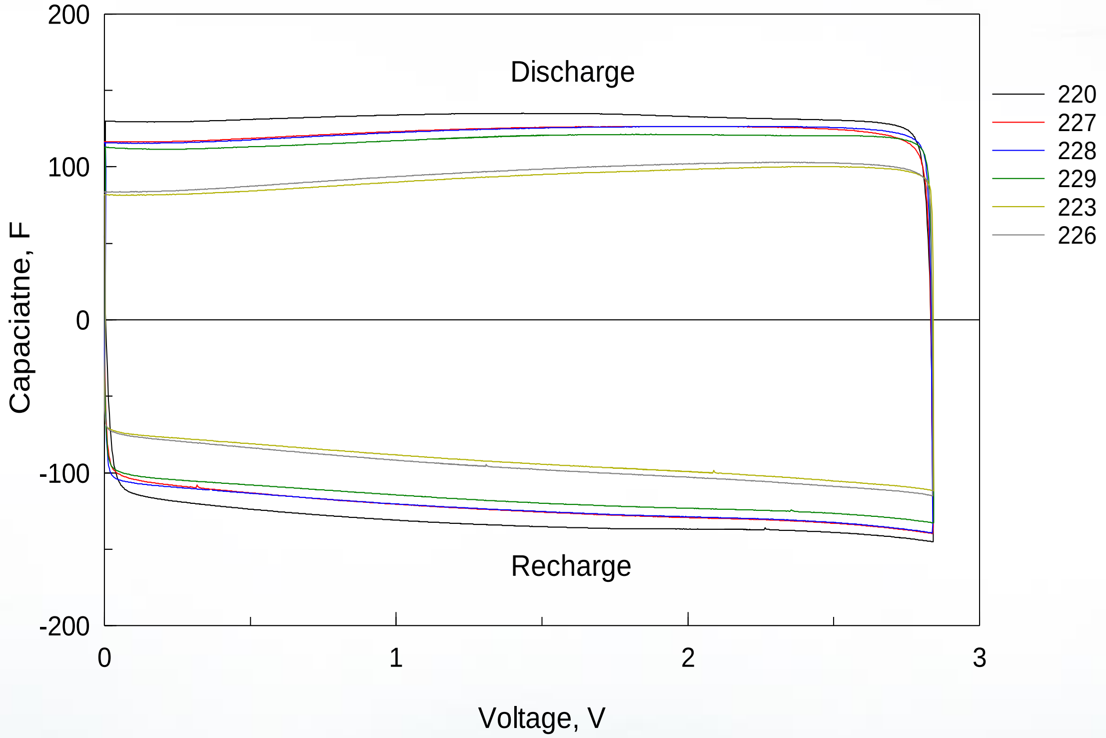
The technical objective of Skeleton Technologies in the ESA supported ultracapacitor development project was to create the ~100F ultracapacitor prototype (we called it SpaceCap) with a superior energy and power density packed in the casing, which would be robust, but potentially radiation resistant.



Summary table of prototypes

Type	SpaceCap #	Anode/Cathode	Electrode thickness [µm]	Al foil thickness [µm]	Total weight [g]
HE-1	220	TiC-1/TiC-2	130/144	11	25.0
HE-2	230	TiC-1/TiC-2	130/144	11	25.6
ME-2	227	TiC-6/TiC-3	90/100	11	25.5
ME-3	228	TiC-6/TiC-3	90/100	11	25.3
ME-4	229	TiC-3/TiC-3	90/100	11	25.3
HP-1	223	TiC-3/TiC-4	60/66	14	25.4
HP-2	226	TiC-3/TiC-4	60/66	14	25.2

C-V curves of prototypes



Energetic characteristics of prototypes

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SpaceCap #	At DC current		EIS (2.85V)		Energy density		Power density	
	C [F]	R [mΩ]	C [F]	R [mΩ]	[Wh/L]	[Wh/kg]	[kW/kg]	[kW/L]
230 HE	132.5	4.5	132.5	3.6	10.5	5.8	17.7	32
220 HE	136.1	4.4	132.9	3.6	10.5	6.0	18.3	32
227 ME	124.6	3.3	121.2	2.9	9.8	5.5	24.1	43
228 ME	124.5	2.4	124.7	1.8	9.8	5.5	33.1	59
229 ME	121.6	2.5	121.2	1.8	9.6	5.4	32.1	57
223 HP	97.5	1.9	100.7	1.2	7.9	4.5	42.7	75
226 HP	101.1	1.8	103.3	1.2	8.1	4.6	44.9	79
BCAP0100	100				5.9	4.4	5.3	7.1
BCAP0150	150				6.1	4.7	3.7	4.8
RSC2R7107SR	100				5.9	5.1	24.6	28.8

Temperature dependence of prototypes

SpaceCap #	**-25°C**		**+25°C**		**+60°C**	
	C [F]	R [mΩ]	C [F]	R [mΩ]	C [F]	R [mΩ]
230 HE	123.2	7.9	132.5	4.5	-	-
227 ME	121.3	7.2	124.6	3.3	124.2	2.2
223 HP	97.0	3.8	97.5	1.9	96.6	1.6

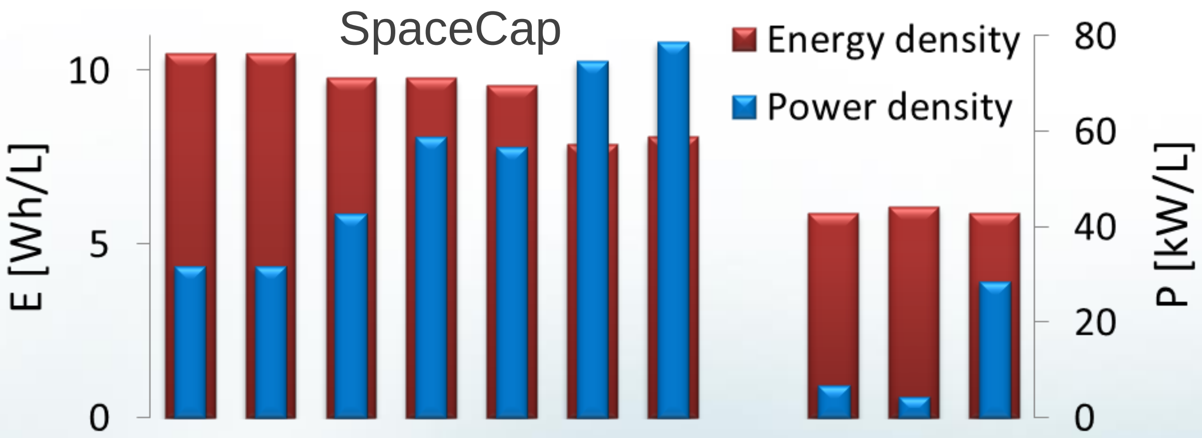
Summary

The HE prototypes - the energy density of 10.8 Wh/L,

which exceeds by ~50% of commercially available devices with similar energy capacity.

The HP prototypes - the power density of 75kW/L,

which exceeds by ~3 times the commercially available devices with similar energy capacity.



Thank You !

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