First characterization tests and planned experiments on diamonds and diamond based composites for luminescence applications

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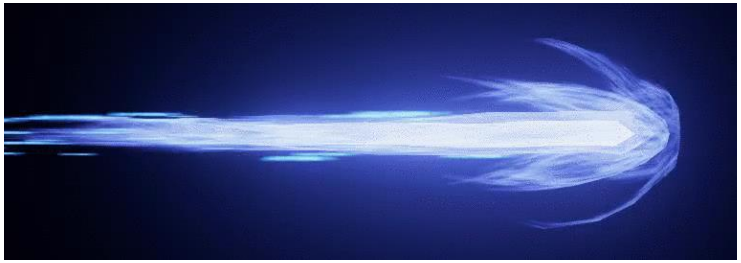
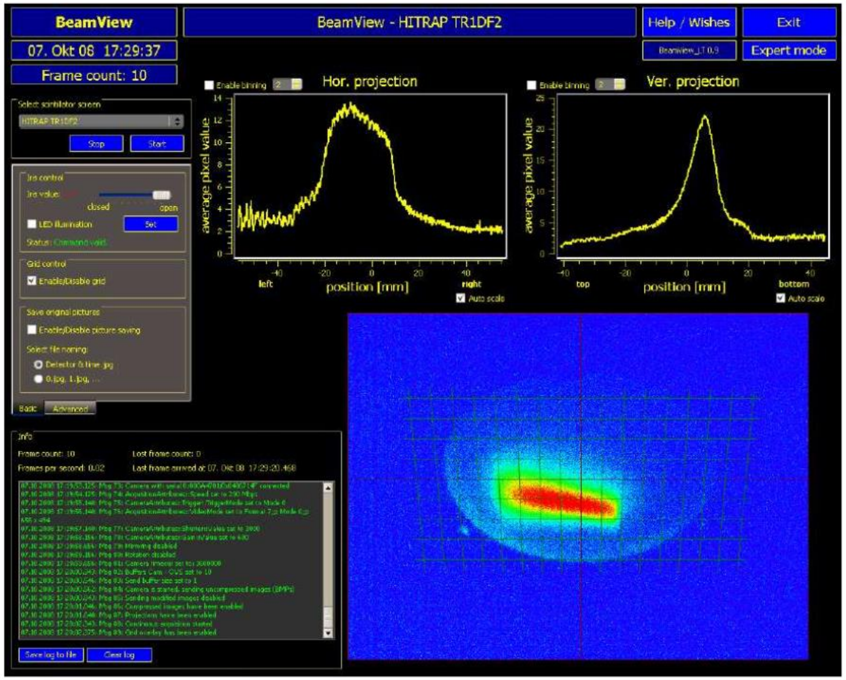
Outline

- Motivation
- Beam profile measurement
- Scintillation-based luminescence screens
- Copper/Diamond composite
- Optimization of diamond/metal-matrix composites
- Planned experiments at GSI

Motivation
Beam profile measurement





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Beam → Black Magic → Beam profile

Motivation
Beam profile measurement techniques

- Luminescence screens
- Optical transition radiation screens
- Beam induced fluorescence monitors
- Wire scanners
- Secondary electron emission grid
- Ionization profile monitors

Direct optical

Indirect optical

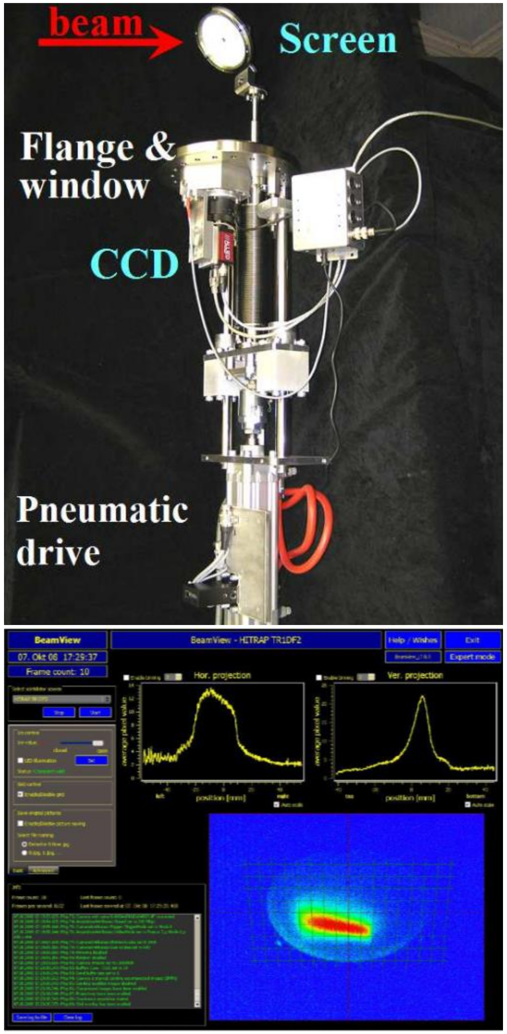
Indirect electrical measurement

- Challenges (applying to all):
  - Linear signal response w.r.t. beam intensity
  - Fast
  - Radiation-hard
  - Thermomechanical robustness
  - Compact and „easy“ to realize

Luminescence screens

- Scintillating ceramics
  - Alumina
  - Cromox (chromium doped alumina)
  - Zirconia stablized magnesium oxide
  - Aluminum nitride
  - Boron nitride

- Limitations:
  - Beam intensity
    - Thermal stresses (CW)
    - Thermomechanical robustness (AC)
  - Temporal response (~ms response)



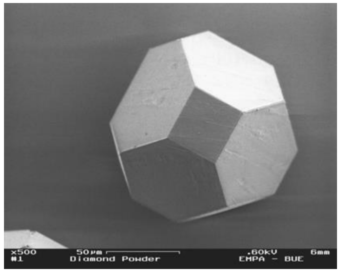
GSI scintillating luminescence screen and beam profile (courtesy of P. Forck)

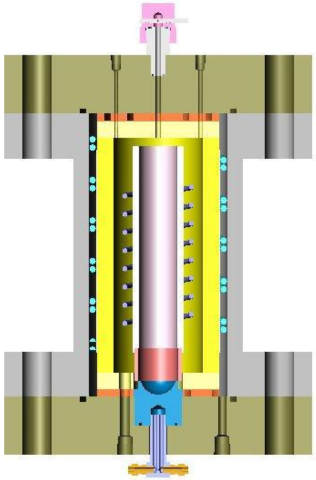
Copper diamond composite

- Developed by RHP-Technology (Austria)
  - 60 vol-% diamond
  - 39 vol-% copper
  - 1 vol-% boron

- Produced by hot pressing

- Selected diamond grid
  - Mono-crystalline diamond
  - Low nitrogen content
  - Relatively large size (>100µm(

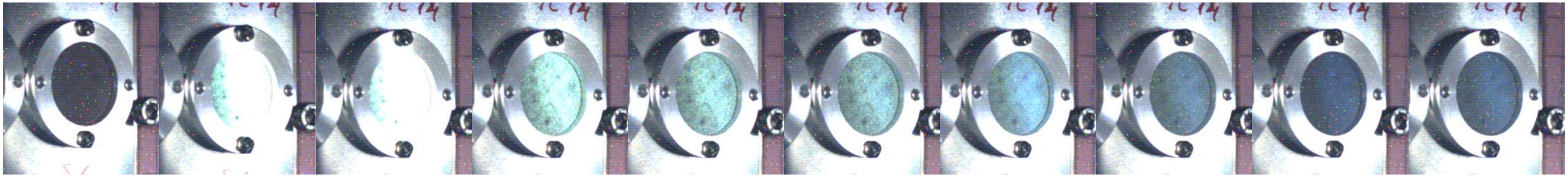




Copper Diamond	
Density (g·cm^{-3})	5.4
Melting point (°C)	1085
Thermal conductivity (W·m^{-1}K^{-1})	490
CTE / 20°C (10^{-6} K^{-1})	6
Flex. Young's modulus (GPa)	220
Flex. Ultimate strength (MPa)	70

CuCD – SHI-induced luminescence

- Observation of beam-induced luminescence with commercial remote-control CCD camera



No beam

Start of Irradition

2×10^{11} i/cm^2

4×10^{11} i/cm^2

6×10^{11} i/cm^2

8×10^{11} i/cm^2

1×10^{12} i/cm^2

2×10^{12} i/cm^2

5×10^{12} i/cm^2

1×10^{13} i/cm^2

1 GeV ^{209}Bi / 4×10^{9} i/cm^{2}·s → **Cu-CD**: Courtesy of M.Tomut

- Already used as beam position monitor for 200-300 MeV/n ^{150}Sm & ^{238}U beams for SIS18 experiments

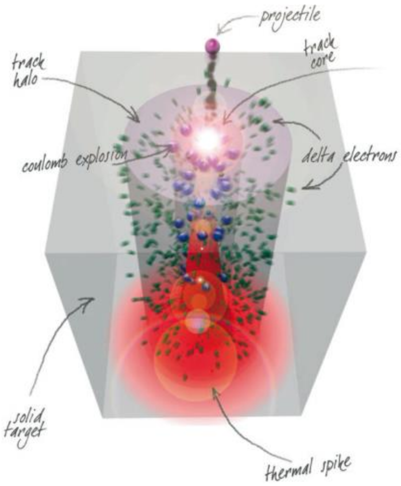
Use of **non-optimized** material!

CuCD – SHI-induced luminescence

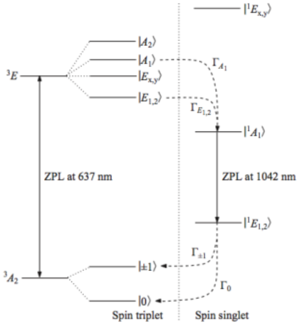
- SHI passage creates shower of delta electrons
- Excitation of crystallographic defects with electronic structure

- Most common defects (impurities) in diamonds:
  - Extrinsic defects: nitrogen
  - Intrinsic defects: carbon vacancies

- Nitrogen-vacancy colour center:
  - NV^0 - 575 nm (19 ns lifetime)
  - NV^- - 638 nm (11 ns lifetime)



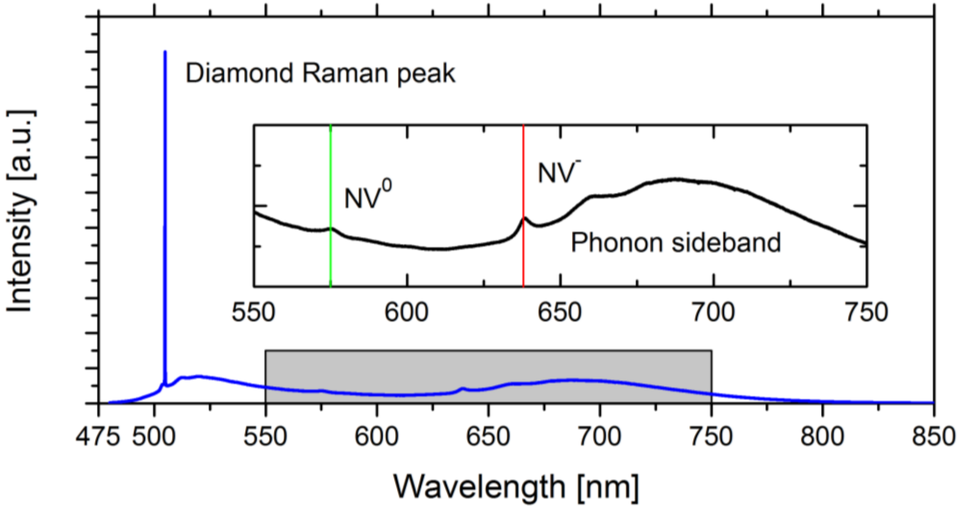
Marek Skupinksi, Nanopatterning by Swift Heavy Ions, PhD Thesis, Uppsala, 2006.



10.1103/PhysRevB.91.165201

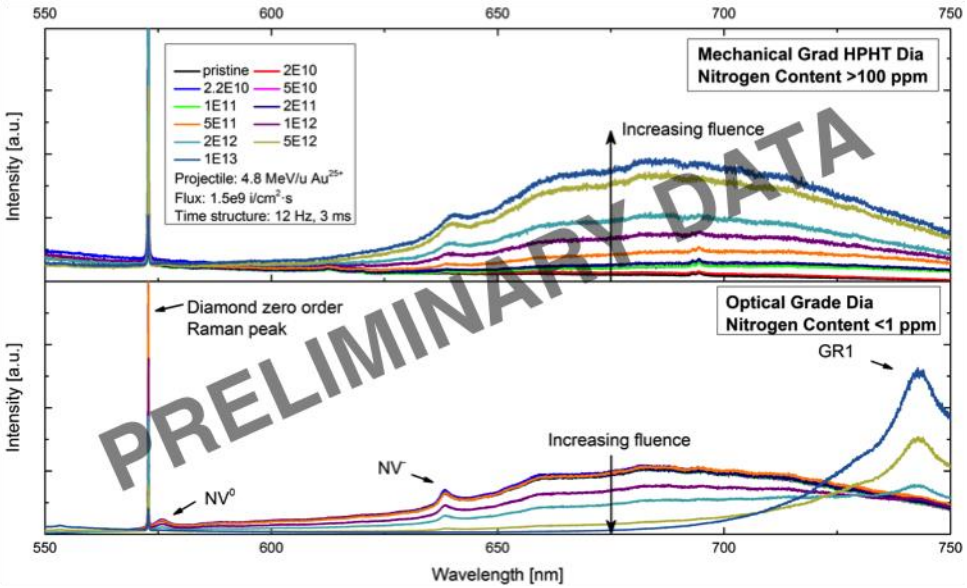
CuCD – SHI-induced luminescence fluence dependence

Pristine



- Presence of nitrogen in unirradiated CuCD

Irradiated



- Sensitivity to quenching depends on nitrogen content

Optimization needed!

CuCD – Limitations

- Radiation-hardness / beam robustness proven
  - GSI UNILAC short pulse uranium beam ✓
  - HiRadMat: 288 full intensity bunches from SPS ✓
  - GSI SIS18 focused fast-extracted uranium beam ✗
    - 198 MeV/n ^{238}U, 1·10 i/p, 100 ns, σ=1 mm
- Mechanical strength limited by boron carbides
- Luminescence quenching

Diamond / metal matrix optimization routes
Matrix

- Copper:
  - Medium-Z
  - Medium density
  - Good thermomechanical properties
  - „Low“ melting point

- Possible alternatives:
  - Titanium (alloys)
  - Aluminum (alloys) (for UNILAC energies)

Diamond / metal matrix optimization routes
Matrix

	Copper	Titanium	Ti-64	Aluminum
Atomic number	29	22		13
Density (g·cm^{-3})	8.96	4.51	4.42	2.7
Melting point (°C)	1085	1668	1600	657
Thermal conductivity (W·m^{-1}K^{-1})	401	22	7	240
CTE / 20°C (10^{-6} K^{-1})	16	9	8.6	23
Young’s modulus (GPa)	120	120	120	70
Tensile strength (MPa)	200	140	Up to 950	Up to 500

Diamond / metal matrix optimization routes
Matrix

- Challenges:
  - Diamond / metal interface stability
    - Beam-induced sputtering?

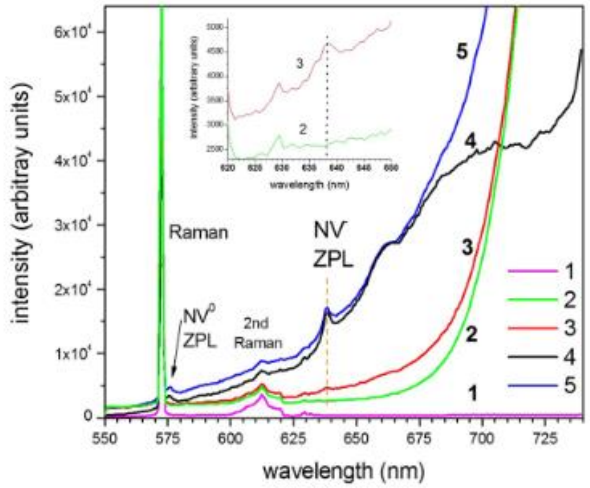
  - Titanium:
    - Low conductivity
    - Reactivity with diamonds
    - Influence of different processing parameters

  - Aluminum:
    - Only suitable for UNILAC energies and pulse lengths
    - Beam is stopped in the target

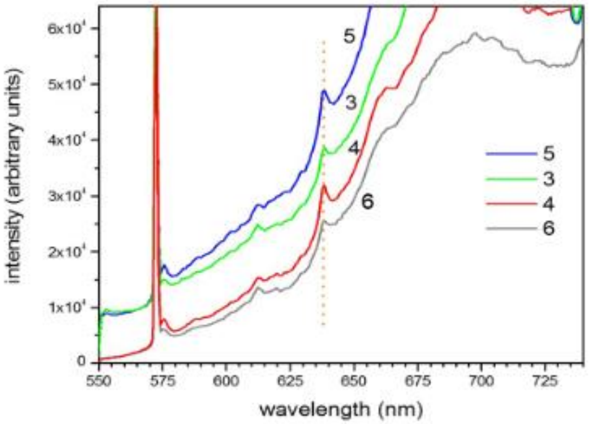
Diamond / metal matrix optimization routes
Diamonds

- Size distribution
  - Grid mixing
- Dispersion
  - Surface or bulk dispersion
- Volume-fraction
- Type of diamond
  - Low/high nitrogen content
  - Mixing of different grades

- Processing parameters
  - Thermal annealing or electron irradiation might activate more NV colour centers



Annealing

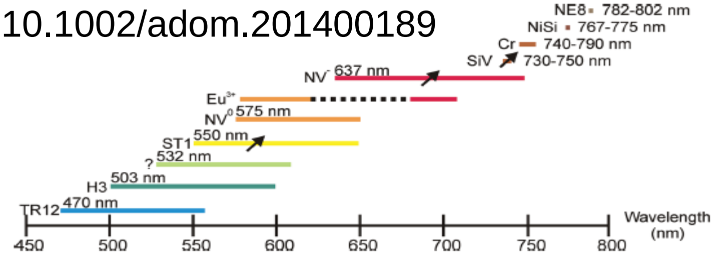


10.1063/1.4903075

Diamond / metal matrix optimization routes
Colour centers

- Tailored diamonds with different colour centers

10.1002/adom.201400189



- Optimized:
  - Emission wavelength
  - Intensity
  - „Radiation-hardness“ / quench sensitivity
  - Temporal resolution

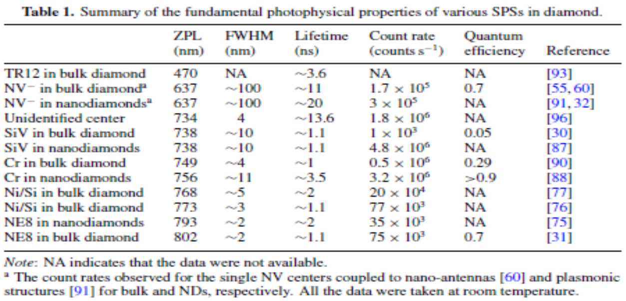


Table 1. Summary of the fundamental photophysical properties of various SPSs in diamond.

	ZPL (nm)	FWHM (nm)	Lifetime (ns)	Count rate (counts s^{-1})	Quantum efficiency	Reference
TR12 in bulk diamond	470	NA	~3.6	NA	NA	[93]
NV$^-$ in bulk diamond[a]	637	~100	~11	1.7×10^5	0.7	[55, 60]
NV$^-$ in nanodiamonds[a]	637	~100	~20	3×10^5	NA	[91, 32]
Unidentified center	734	4	~13.6	1.8×10^6	NA	[96]
SiV in bulk diamond	738	~10	~1.1	1×10^3	0.05	[30]
SiV in nanodiamonds	738	~10	~1.1	4.8×10^6	NA	[87]
Cr in bulk diamond	749	~4	~1	0.5×10^6	0.29	[90]
Cr in nanodiamonds	756	~11	~3.5	3.2×10^6	>0.9	[88]
Ni/Si in bulk diamond	768	~5	~2	20×10^4	NA	[77]
Ni/Si in bulk diamond	773	~3	~1.1	77×10^3	NA	[76]
NE8 in nanodiamonds	793	~2	~2	35×10^3	NA	[75]
NE8 in bulk diamond	802	~2	~1.1	75×10^3	0.7	[31]

Note: NA indicates that the data were not available.

[a] The count rates observed for the single NV centers coupled to nano-antennas [60] and plasmonic structures [91] for bulk and NDs, respectively. All the data were taken at room temperature.

10.1088/0034-4885/74/7/076501

- Identify:
  - Most suitable colour center
  - Processing routes („exotic“ colour centers can only be produced by doping → large area doping needed)

Planned experiments at GSI
Off-line

- Different grades and sizes of (nano-)crystalline diamonds
  - High-pressure/high-temperature
  - Chemical vapor deposited
  - Laser-synthesized
  - Detonation nanodiamonds

    Activated fluorescent „ultra-bright“ nanodiamonds for bio-medical appl.

Powders & Suspensions

nm to mm size

- Alternative approaches
  - Scintillating ceramic / metal composite
  - Nano-crystalline multi-component scintillation ceramics
- Investigation of:
  - Luminescent properties
    - Photo- & cathodoluminescence, Raman spectroscopy
  - Thermal stability
    - In-situ high temperature Raman spectroscopy
  - Beam stability
    - Electron Irradiation

Planned experiments at GSI
On-line

- Diamonds
  - Doping of high purity diamonds
    - Activation of „exotic“ colour centers
  - Nitrogen-free to high nitrogen content diamonds
    - Controlled nitrogen doping
  - Nanodiamonds
    - Beam stability / beam-induced structural changes
    - Size effects

- Diamond/metal composites
  - High LET ion-irradiation (close to the Bragg peak):
    - Thermal and luminescent robustness
  - High-energy fast extraction
  - Laser-driven ultra-short proton pulse (~200-400 ps) irradiation
    - Temporal response

Thank you!

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD-2, grant agreement no.312453

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.