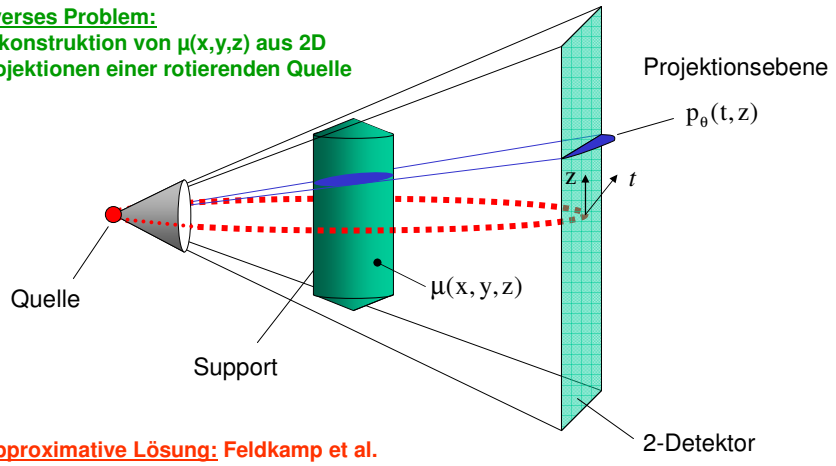
Weitere Tomographieverfahren

Mikro- und Kegelstrahl-CT
Elektronenstrahl-CT und LAT
Optische CT
Elektrische Impedanztomographie
Optische Streulichttomographie

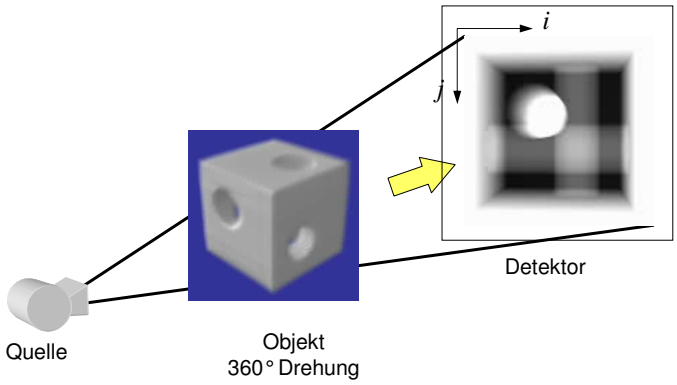
Kegelstrahl-CT

Inverses Problem:
Rekonstruktion von μ(x,y,z) aus 2D Projektionen einer rotierenden Quelle



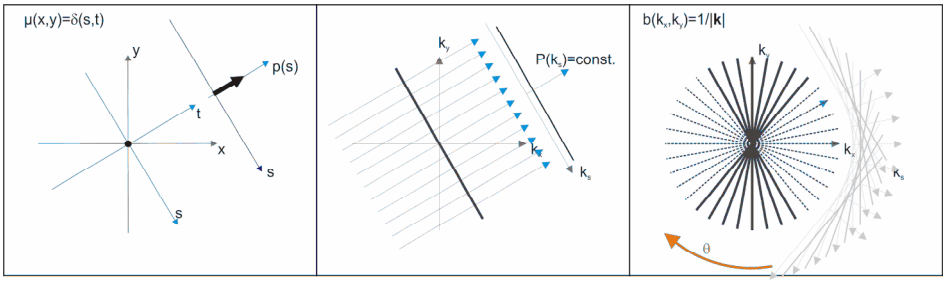
Approximative Lösung: Feldkamp et al.

Kegelstrahlrekonstruktion - Vorwärtsprojektion



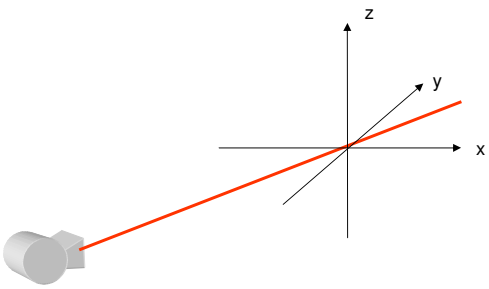
Kegelstrahlrekonstruktion - Abtastung

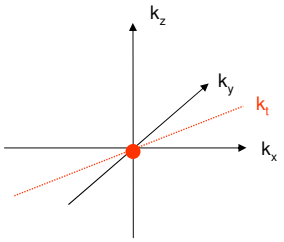
Wir erinnern uns an das Zentralschnitttheorem:



Kegelstrahlrekonstruktion - Abtastung

Erweiterung des Zentralschnitttheorems ins Dreidimensionale:

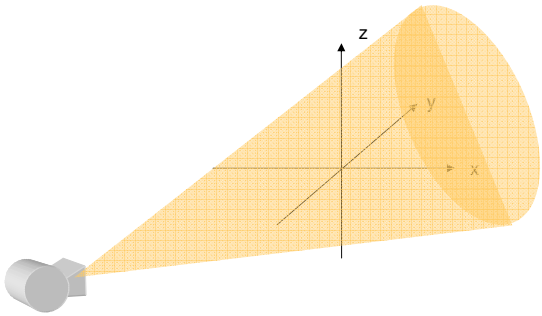


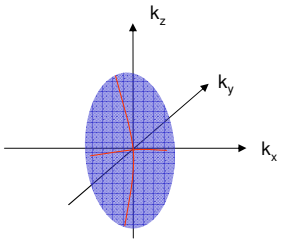


Integration entlang des Strahls bedeutet Abtastung des Frequenznullpunktes im Fourierraum durch den Strahl

Kegelstrahlrekonstruktion: k-Raum-Abtastung

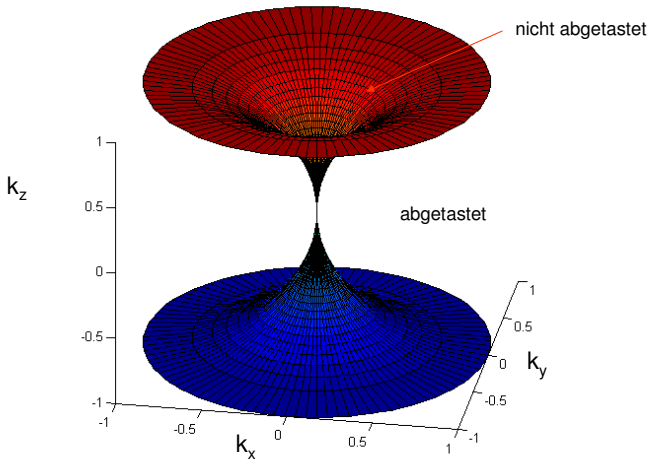
Erweiterung des Zentralschnitttheorems ins Dreidimensionale:





Für die Kegelstrahlen einer Strahlerposition ergibt sich eine begrenzte Kugelschale für das abgetastete Gebiet des Fourierraumes.

Kegelstrahlrekonstruktion: k-Raum-Abtastung

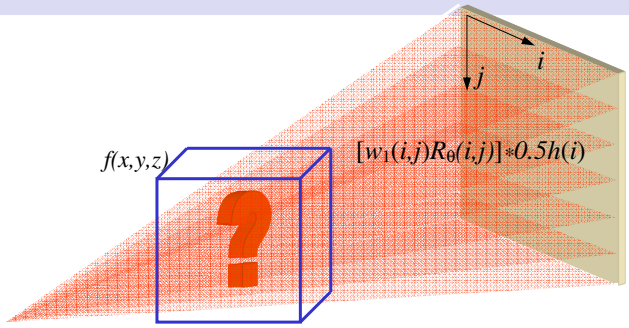


Kegelstrahlrekonstruktion nach Feldkamp et al.

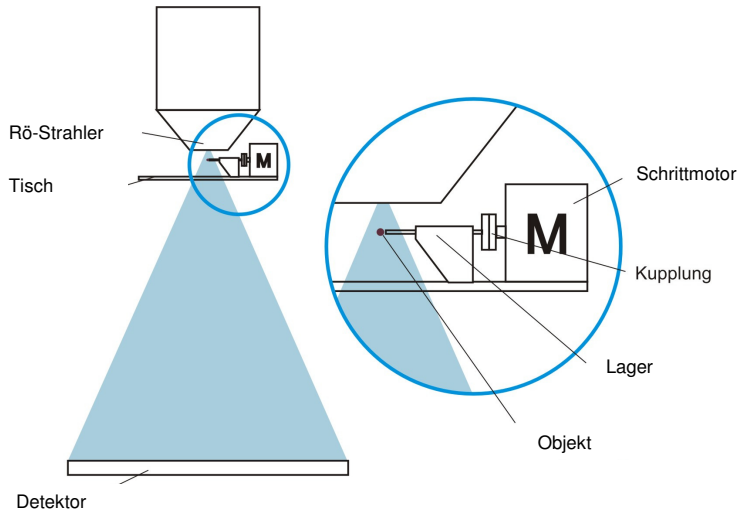
[Feldkamp et al., J. Opt. Soc. Am A, Vol 1(6), 612-9, 1984]

$$f(x,y,z) \approx \int_{\theta=0}^{2\pi} \iiint_{z\ y\ x} w_2(x,y,z,\theta) \left\{ \underbrace{[w_1(i,j)\cdot R_\theta(i,j)]}_{\text{weighting}} * \underbrace{\frac{1}{2} h(i)}_{\text{filtering}} \right\} \underbrace{\delta(b(i,j,x,y,z,\theta))}_{\text{interpolation}} dx\,dy\,dz\,d\theta$$

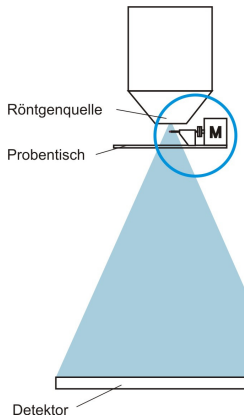
weighting



Mikro-CT von Polymerpartikeln



µ-Tomographie
Feinfokustechnik

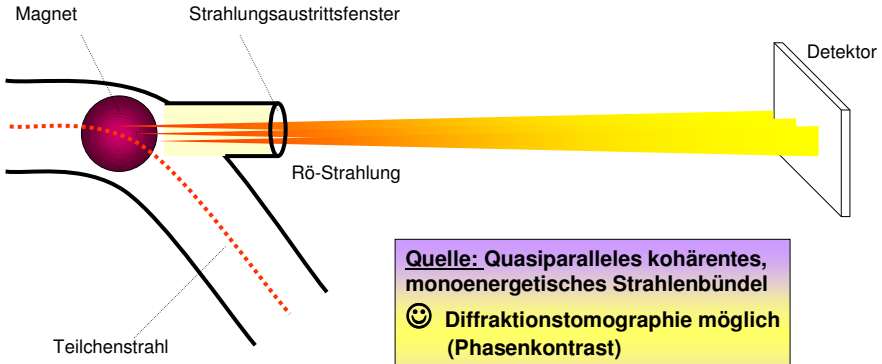


<u>Quelle:</u> Feinfokusstrahler

☺ **Perspektivische Vergrößerung, wählbare Auflösung**

☺ **Einfacher Aufbau**

µ-Tomographie
- Synchrotronstrahlung -

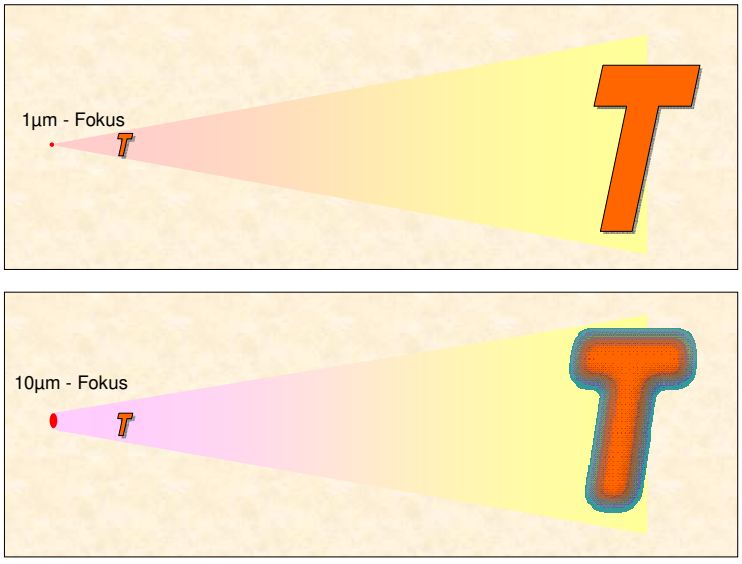


Quelle: Quasiparalleles kohärentes, monoenergetisches Strahlenbündel

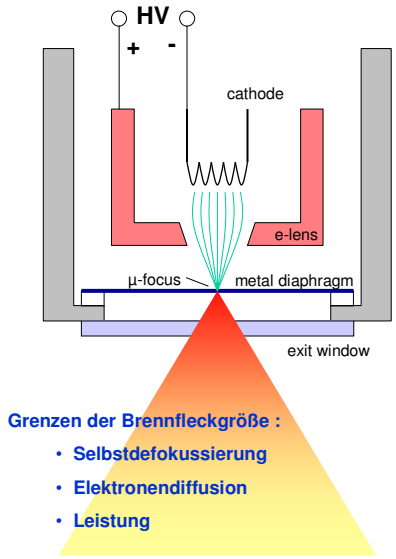
☺ Diffraktionstomographie möglich (Phasenkontrast)

☹ Erfordert hochauflösenden Rö-Detektor

Quellfokus bestimmt räumliches Auflösungsvermögen



Nano-Fokus-Strahler

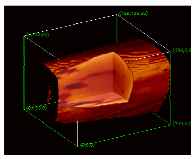


Grenzen der Brennfleckgröße :

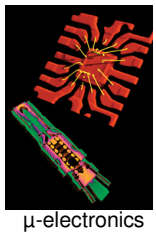
- **Selbstdefokussierung**
- **Elektronendiffusion**
- **Leistung**

µ-Tomography

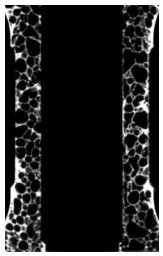
- today's applications -



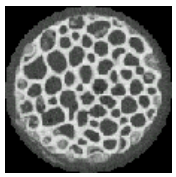
materials research
(minerals, concrete, wood, etc.)



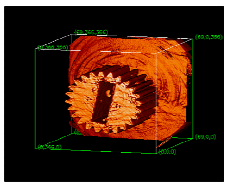
µ-electronics



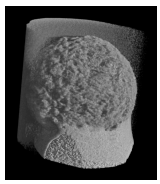
metallic foams



animal diagnostics

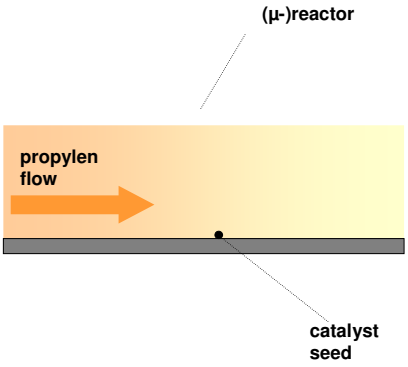


µ-mechanics

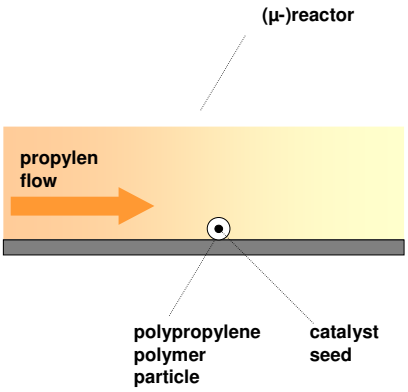


polymer particles

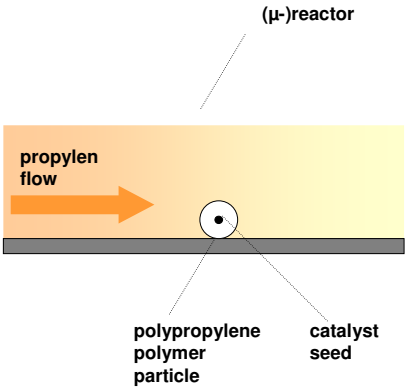
Polymer particles



Polymer particles



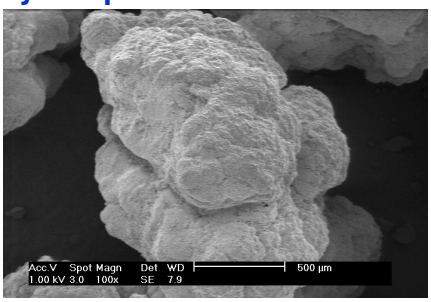
Polymer particles

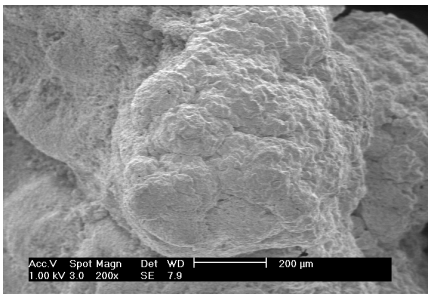


Polymer particles

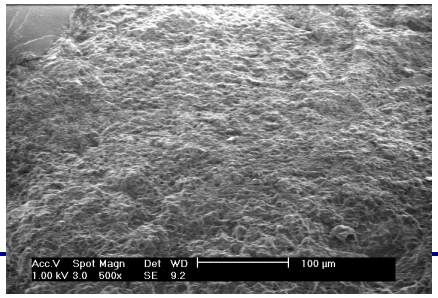
Polymer particles

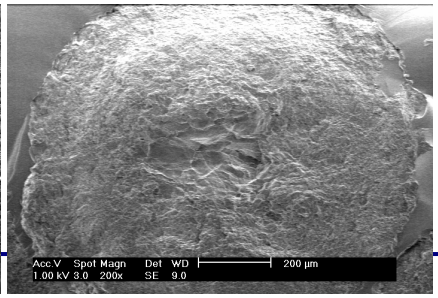
Surface SEM





Cross sectional SEM

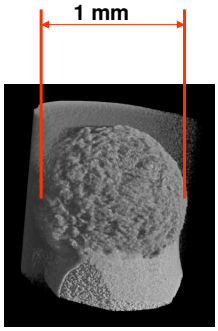




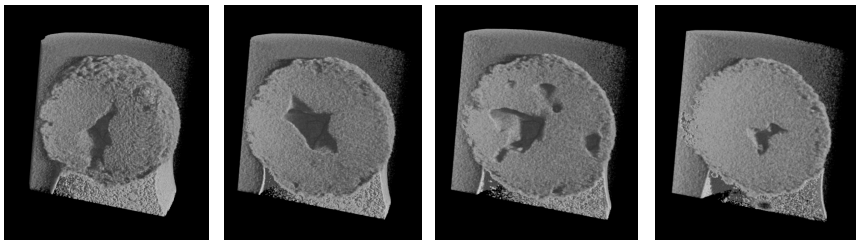
Commercial µ-CT system

Phoenix X-ray GmbH

spot size = 10 µm



Volume CT of polymer particle



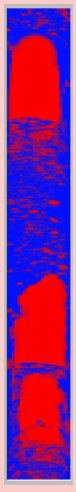
Elektronenstrahl-CT
und
Limited-Angle-Probleme

Schnelle Röntgentomografie

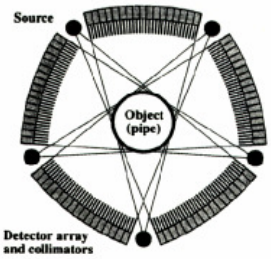
Motivation:

Untersuchung hochdynamischer transienter Dichteveränderungen, z. B.:

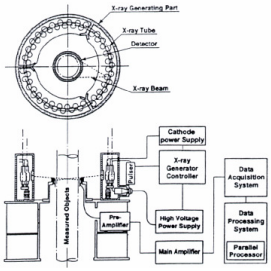
- **Mehrphasenströmungen in Rohrleitungsquerschnitten**
- **Phasenübergänge**
- **Verhalten von Flüssig- und Siedefilmen**
- **Tröpfchen- und Partikelströmungen**



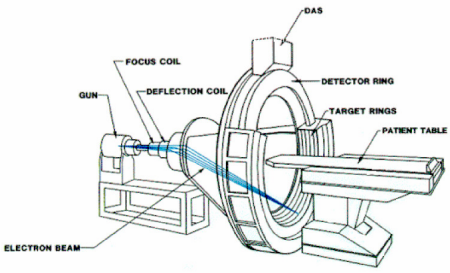
Stand der Technik



Froystein (1999)



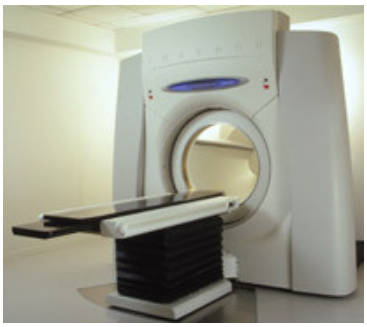
Hori (1997)



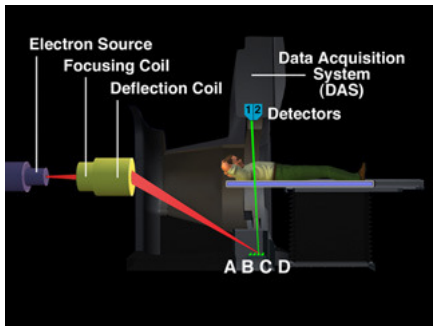
Boyd (1987)

Electron Beam Computed Tomography (EBCT)

- schnelle CT für die Kardiobildgebung -

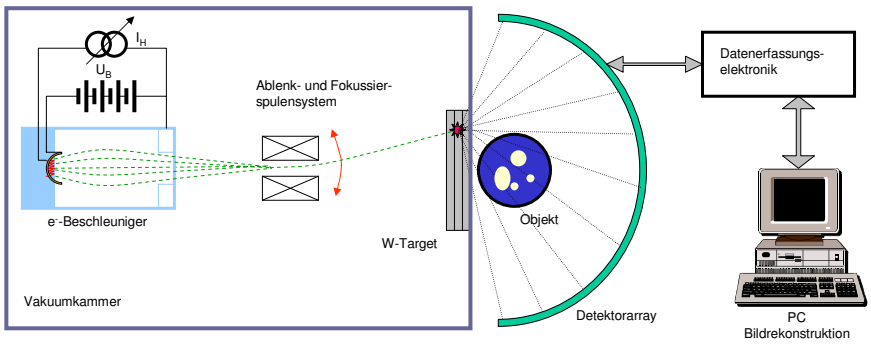


Quelle: Imatron GE, http://www.geimatron.com

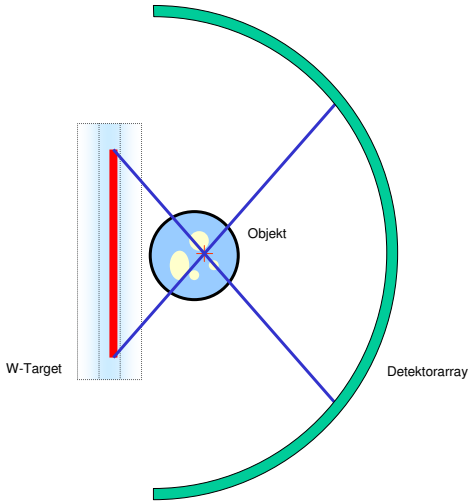


Ultraschnelle Röntgentomografie mit gescanntem Elektronenstrahl

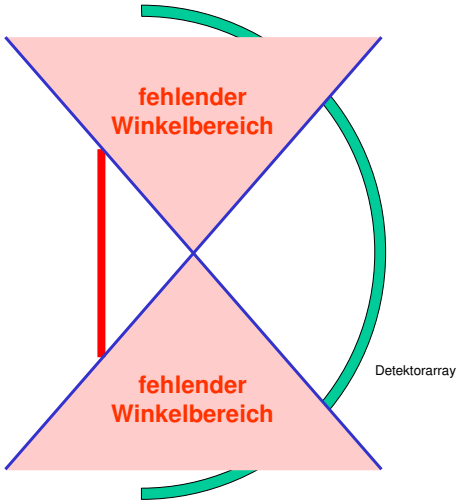
- Erzeugung >1000 Röntgen-Schnittbildern pro Sekunde
- Anwendung der Limited-Angle-Tomographie (LAT)



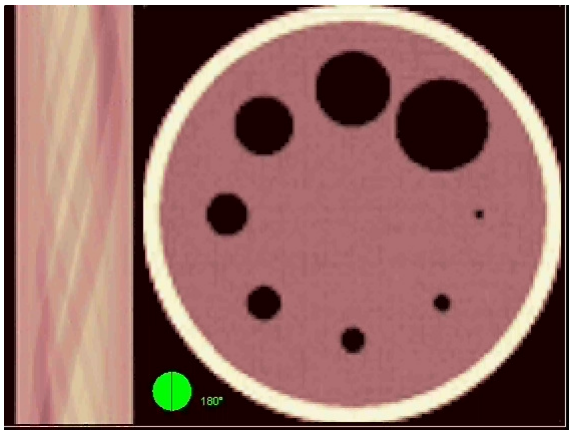
Limited Angle Tomografie



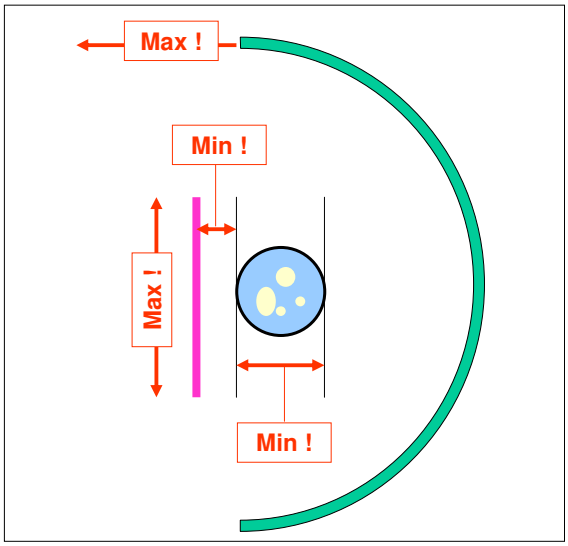
Limited Angle Tomografie



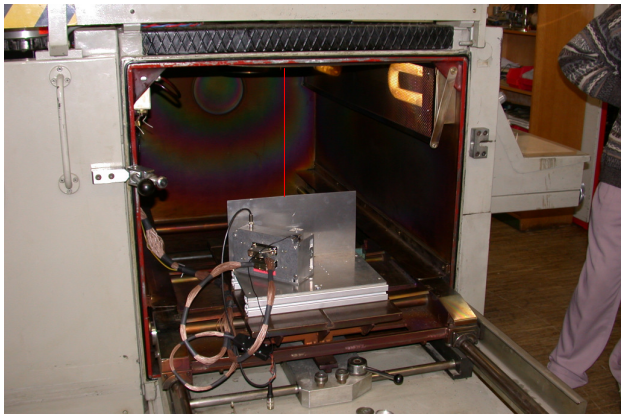
Limited Angle Tomografie



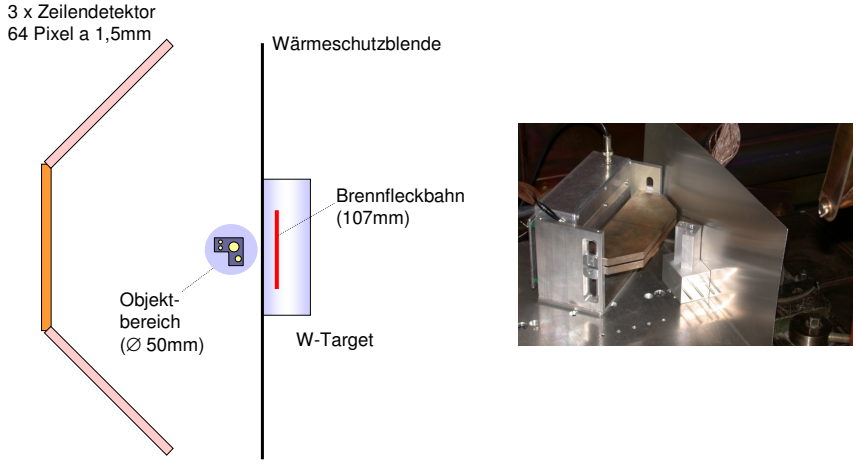
Design- Regeln für LAT



Elektronenstrahl-Schweißbox
IKE Stuttgart

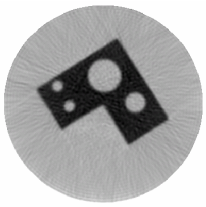


LAT-Experimente
- statische Objekte -

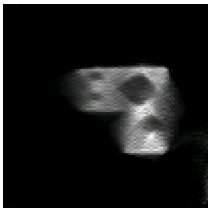


LAT-Experimente
- Materialrekonstruktion an Metallphantom -

Objekt

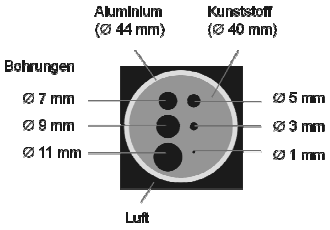


Konventionelle Tomografie

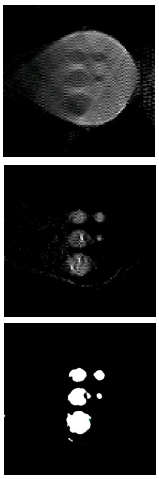


LAT

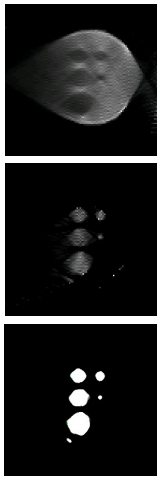
LAT-Experimente
-Kunststoffphantom -



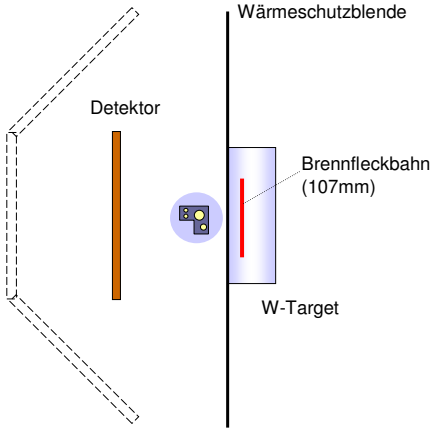
ART



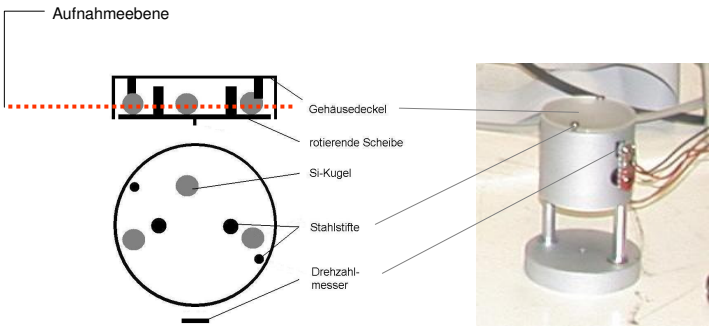
MART



LAT-Experimente
- dynamische Objekte -



LAT-Experimente
- Kugelspiel -



1 Kugel

3 Kugeln

Optische CT

Optische CT – Tomographie mit Licht

Vorteile:

- berührungsfrei
- schnell (>10.000 Bilder/s)
- preiswerte Elektronikkomponenten

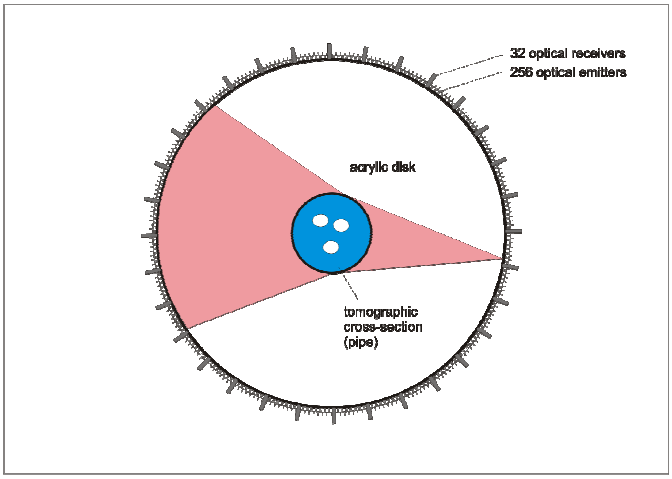
Varianten:

- Messung von Absorption, Streuung, Brechindex
- spektrale Messung – Komponentenanalyse
- Fluoreszenz
- Raman-Streuung

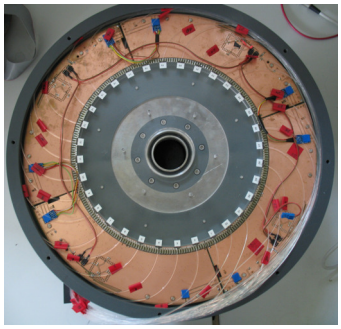
Nachteile:

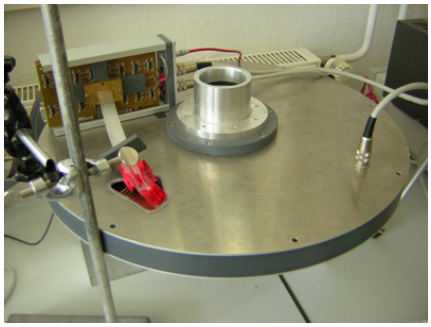
- Nichtlinearität durch Brechindexänderungen (kein exponentielles Lichtschwächungsgesetz für Brechindexvariationen)

Optische CT – Messprinzip

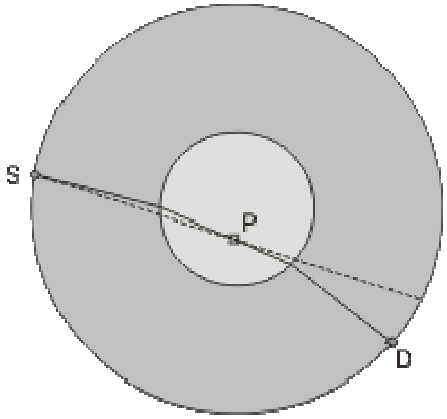


Optische CT – Aufbau

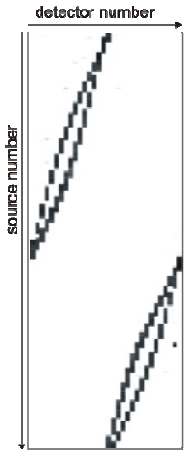


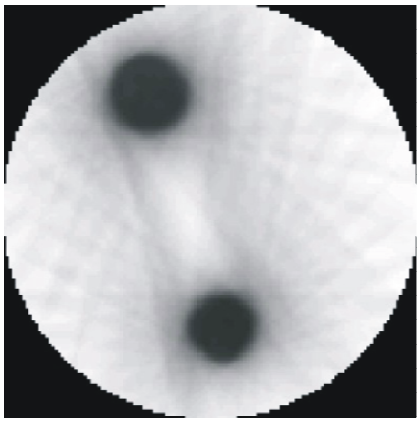


Optische CT – Pixel-Strahl-Zuordnung



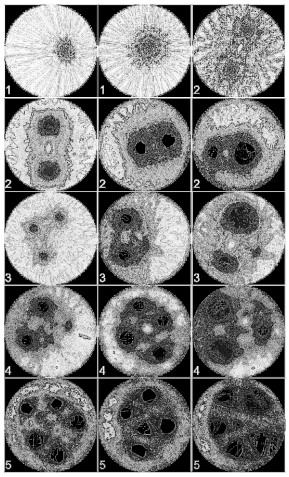
Optische CT



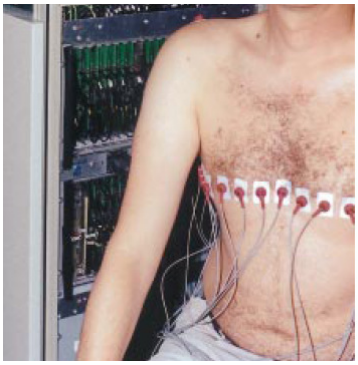


Optische CT

- Beispielaufnahmen „Gasblasen“ -



Elektrische Impedanztomographie (EIT)



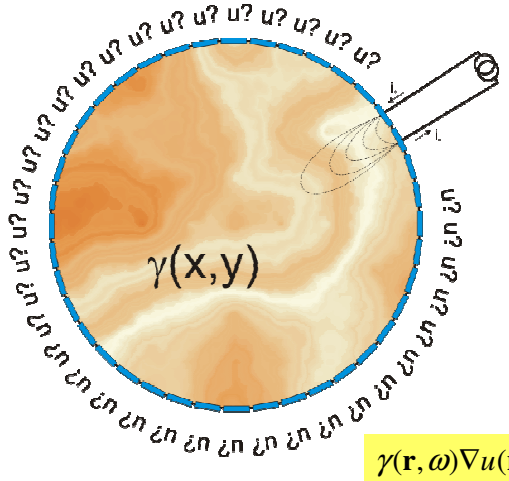
Medizin:
Lungenvolumen, Herzfunktion, Blutfluss, Verdauung, Brustkrebsdiagnostik

Mehrphasenströmungen:
Messung von Phasenverteilungen (Rohrströmung, Wirbelschicht-Reaktor, Rührkessel, etc.)

Geologie: Gesteinsporosität, Wasseradern

NDT: Riss- und Fehlerdetektion

EIT
- Messprinzip -



Laplace-Gleichung:

$$\nabla \cdot \gamma(\mathbf{r},\omega)\nabla u = 0$$

ω - Modulationsfrequenz

$$\gamma = \sigma + i\omega\varepsilon$$

γ - Admittanz
1/γ - Impedanz
σ - Leitfähigkeit
ε - Permittivität

Randbedingungen:

$$\gamma(\mathbf{r},\omega)\nabla u(\mathbf{r},\omega)\mathbf{n}(r) = i(\mathbf{r}) \quad für \quad \mathbf{r} \in \partial\Omega$$

EIT
- Vorwärtsproblem -

Löse PDG: $\nabla \cdot \gamma(\mathbf{r},\omega)\nabla u = 0$

unter Randbedingung:

$$\gamma(\mathbf{r},\omega)\nabla u(\mathbf{r},\omega)\mathbf{n}(r) = i(\mathbf{r}) \quad für \quad \mathbf{r} \in \partial\Omega$$

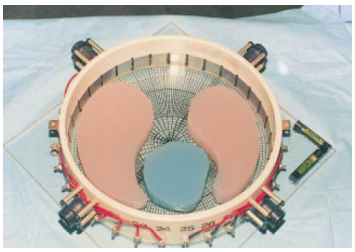
Ergebnis: $u(\mathbf{r},\omega) \quad für \quad \mathbf{r} \in \partial\Omega$

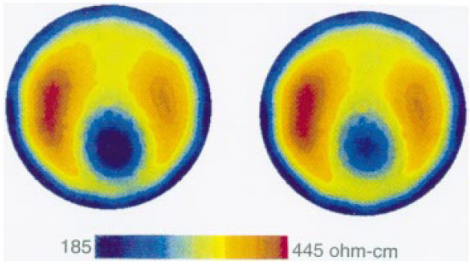
Methode: **FEM oder FDM**

EIT
- Inverses Problem -

Siehe Optische Streulichttomographie

EIT
- Beispiel -





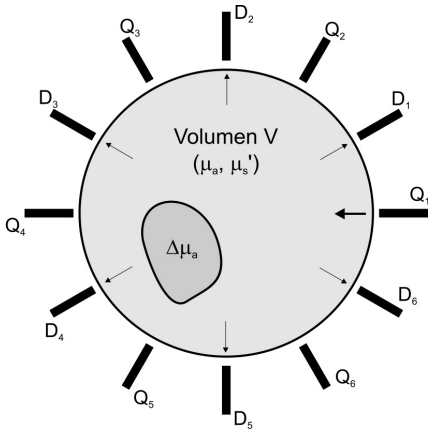
Optische Streulichttomographie (auch Diffusionstomographie)

Anwendungsmöglichkeiten in der medizinischen Diagnostik

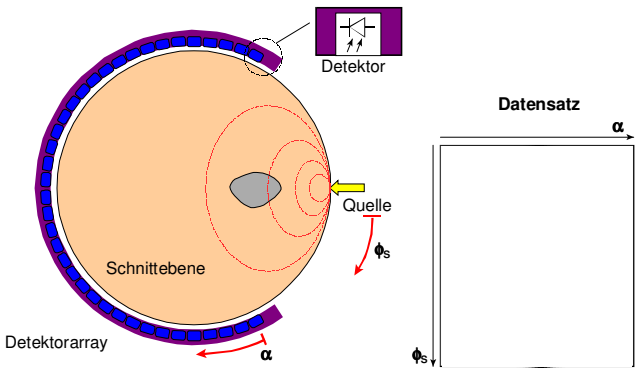
Prinzip:

- Messung des Lichtdurchgangs durch Gewebe und der Absorption an Gewebechromophoren
- Hauptabsorber im Gewebe ist Hämoglobin
- Nutzung spektrometrischer Messverfahren

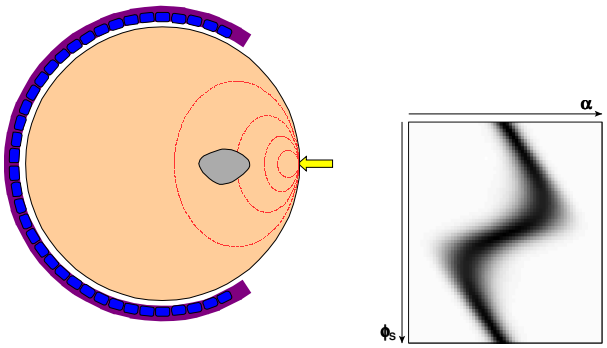
OSCT
- Messprinzip -



Tomographisches Meßprinzip



Tomographisches Meßprinzip



Optisches Diffusionsmodell

Für ausreichend viele Streuereignisse verlieren die Photonen ihr "Richtungsgedächtnis" und genügen den Gesetzen der Diffusion

Reduzierter Streukoeffizient: $\mu_s(\vec{r}) \rightarrow \mu_s'(\vec{r})$

Diffusionskoeffizient: $D(\vec{r}) = \frac{1}{3[\mu_a(\vec{r}) + \mu_s'(\vec{r})]}$

(richtungsintegrale) Photonenflußdichte: $\varphi(\vec{r}) = \int_{4\pi} \varphi_\Omega(\vec{r}, \vec{\Omega}) d\Omega$

stationäre Diffusionsgleichung

$$\{\mu_a(\vec{r}) - \nabla \cdot D(\vec{r}) \nabla\} \varphi(\vec{r}) = s(\vec{r})$$

Optische Diffusionsgleichung

$$\{\mu_a(\vec{r}) - \nabla \cdot D(\vec{r})\nabla\}\varphi(\vec{r}) = s(\vec{r})$$

Lösung

analytisch

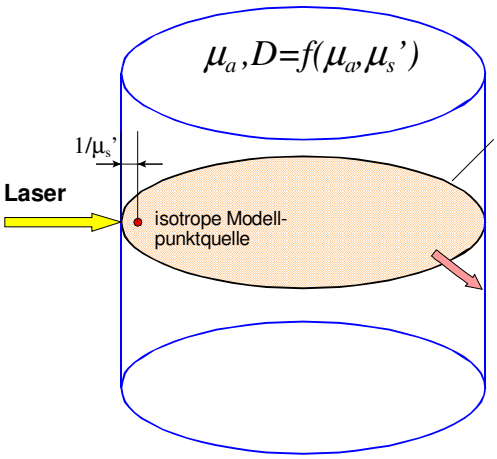
Greensche Funktionen

numerisch

Finite Differenzen Methode (FDM)

Finite Elemente Methode (FEM)

Optisches Diffusionsmodell



Rand:

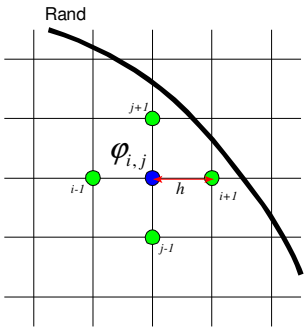
$\varphi(\vec{r}) = 0 \quad (\vec{r} \in S)$

Detektor:

$j(\vec{r}) = -\vec{n}D(\vec{r})\nabla\varphi(\vec{r})$

(Photonenstromdichte)

Finite Differenzen Verfahren
Klassische Methode



Differentialterme

$$\frac{\partial \varphi_{i,j}}{\partial x} \approx \frac{\varphi_{i+1,j} - \varphi_{i-1,j}}{2h}$$

$$\frac{\partial \varphi_{i,j}}{\partial y} \approx \frac{\varphi_{i,j+1} - \varphi_{i,j-1}}{2h}$$

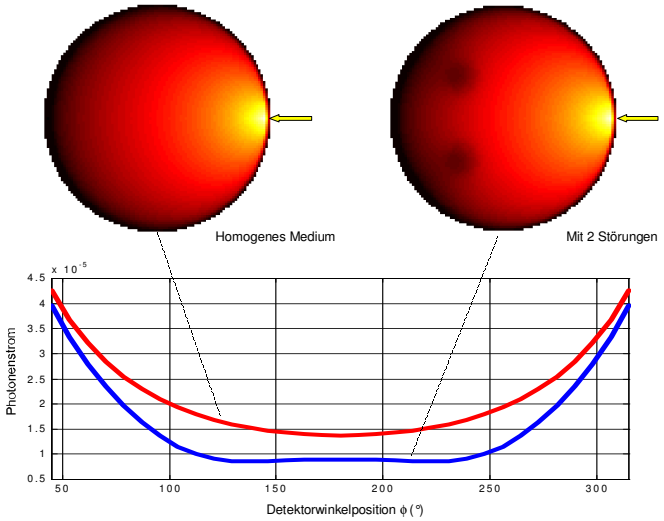
$$\frac{\partial^2 \varphi_{i,j}}{\partial x^2} \approx \frac{\varphi_{i-1,j} + \varphi_{i+1,j} - 2\varphi_{ij}}{h^2}$$

$$\frac{\partial^2 \varphi_{i,j}}{\partial y^2} \approx \frac{\varphi_{i,j-1} + \varphi_{i,j+1} - 2\varphi_{ij}}{h^2}$$

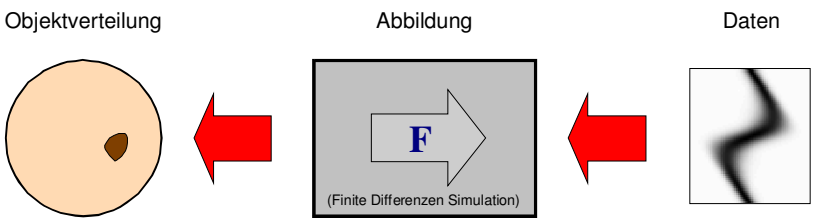
Differenzengleichung

$$\frac{D}{h^2}(\varphi_{i+1,j}+\varphi_{i-1,j}+\varphi_{i,j+1}+\varphi_{i,j-1}-4\varphi_{i,j})-\mu_{aij}\varphi_{i,j}+s=0$$

Finite Differenzen Verfahren
Berechnungsbeispiel



Inverses Problem



$\mu(x,y)$ $\mu=F^{-1}(m)$ $m(\alpha,\phi)$

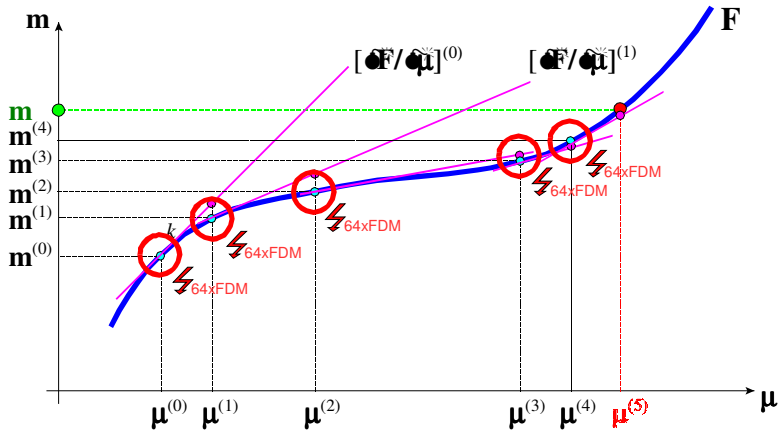
μ_a, D — Verteilung des Absorptions-koeffizientens und/oder des Diffusionskoeffizientens

Photonenstrom auf dem Rand — $j(\alpha,\phi)$

Das Abbildungsproblem der OSCT ist nichtlinear !

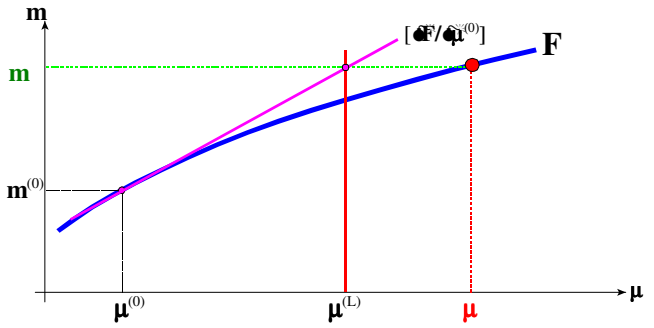
$$\mathbf{F}(\mu_1) + \mathbf{F}(\mu_2) \neq \mathbf{F}(\mu_1 + \mu_2)$$

Lösung des nichtlinearen Problems mit einem Iterationsverfahren ?



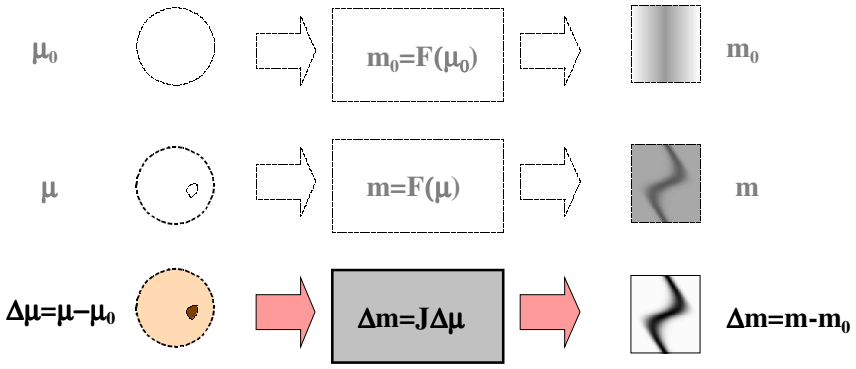
Linearisierung des Abbildungsproblems

Jakobi-Matrix am Arbeitpunkt: $\mathbf{J} = \left[\frac{\partial \mathbf{m}^{(0)}}{\partial \boldsymbol{\mu}^{(0)}}\right]$



Inverse Berechnungsvorschrift: $\boldsymbol{\mu}^{(L)}=\boldsymbol{\mu}^{(0)}+\mathbf{J}^{-1}[\mathbf{m}^{(NL)}-\mathbf{F}\mathbf{m}^{(0)}]$

Meßdaten und Objektverteilung für das linearisierte Problem



Objektverteilung:

$\Delta\mu_a(x,y)$

$\Delta D(x,y)$

Meßdaten:

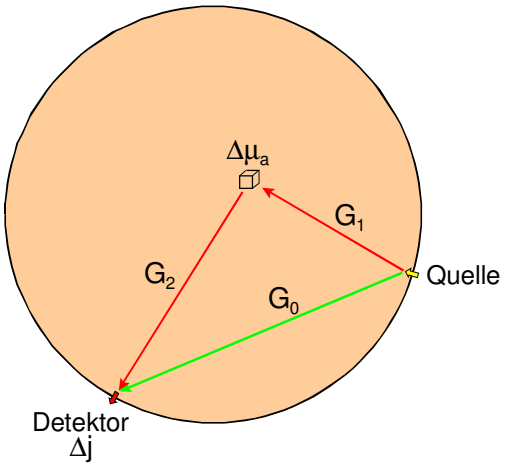
$\Delta m(\alpha_i,\phi_i)$

Berechnung von Bildgebungsoperatoren

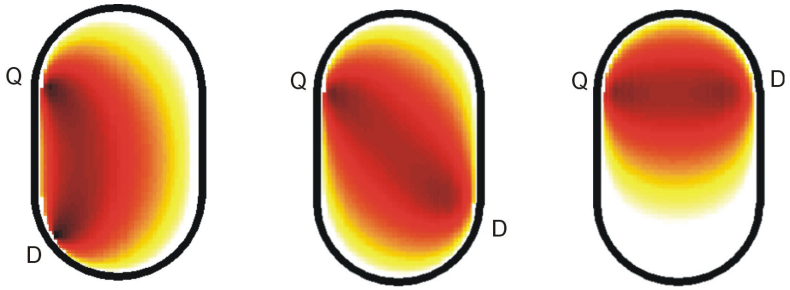
Störungstheoretischer Ansatz

$\Delta j = \Delta\mu_a$

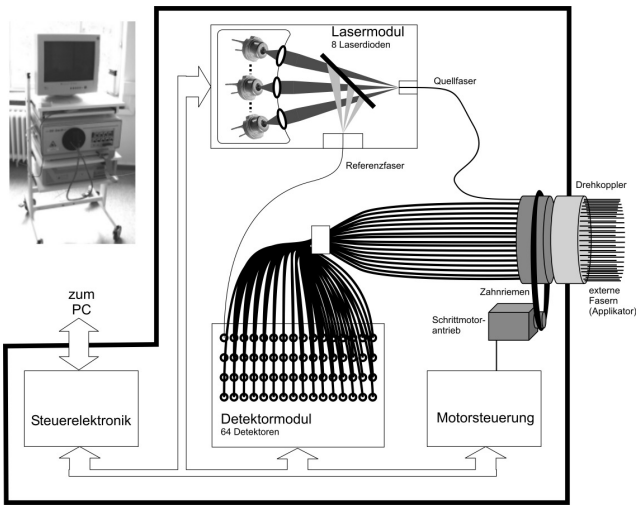
$\Delta j = G_1 G_2 \, \Delta\mu_a$



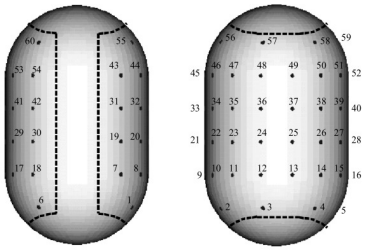
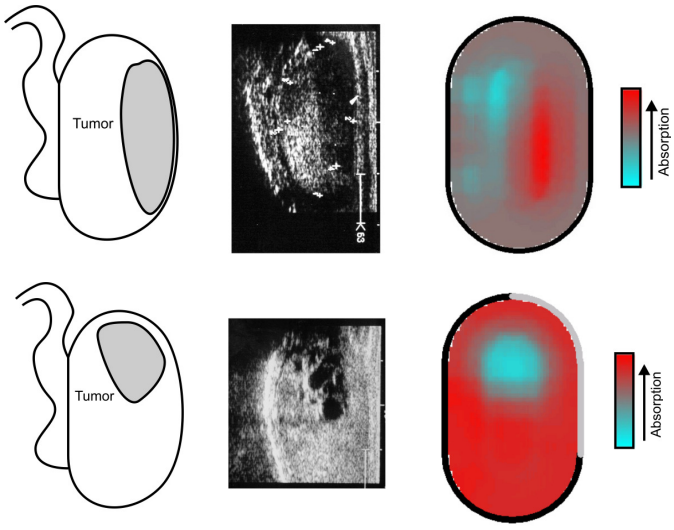
OSCT
- (Pixel-Strahl-)Gewichtsfunktionen -



OSCT
- Laserscanner -



OSCT
- Organapplikator -



OSCT-Beispiel: Diagnostik von Hodenerkrankungen