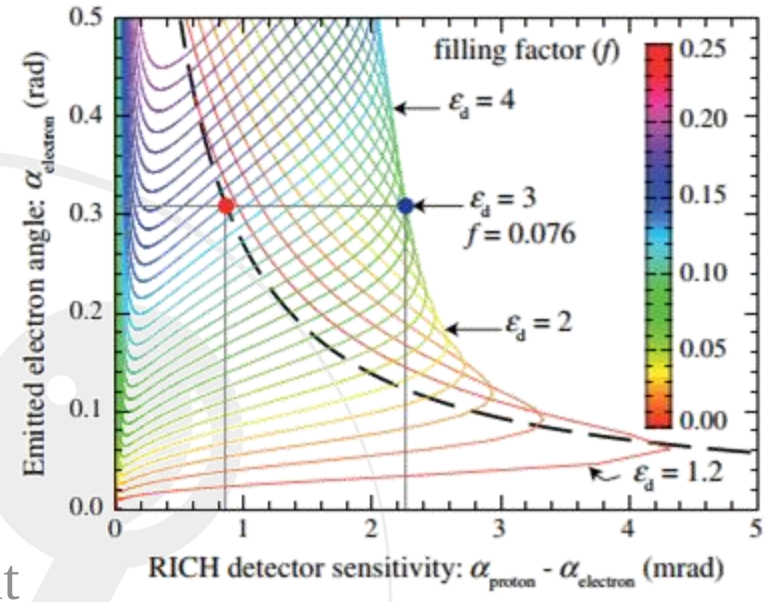
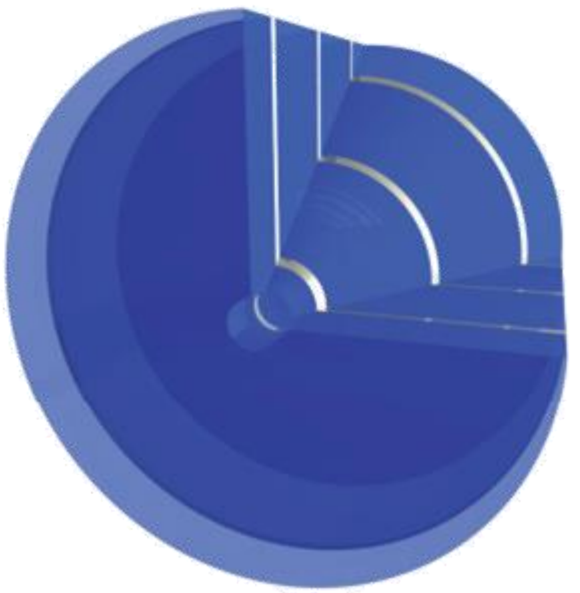
TOME – LDRD

Transformation Optics Meta-Material





Klaus Dehmelt

Outline

1. Project description/Scope/Team
2. Impact and strategic value to the Laboratory's mission
3. Level of innovation
4. Deliverables with corresponding timelines and milestones
5. Budget and budget justification
6. Potential future funding (Beyond LDRD)

Project Description/Scope/Team

Specify

- Transformation Optics ⇨ manipulate optical properties
- Provide solution(s) describing the optical properties

Simulate

- Artificial Neural Network ANN + T-matrix ⇨ Scan over large parameter space
- Identify suitable candidates

Synthesize

- Manufacture substance(s) ⇨ Meta-material
- Quality assurance

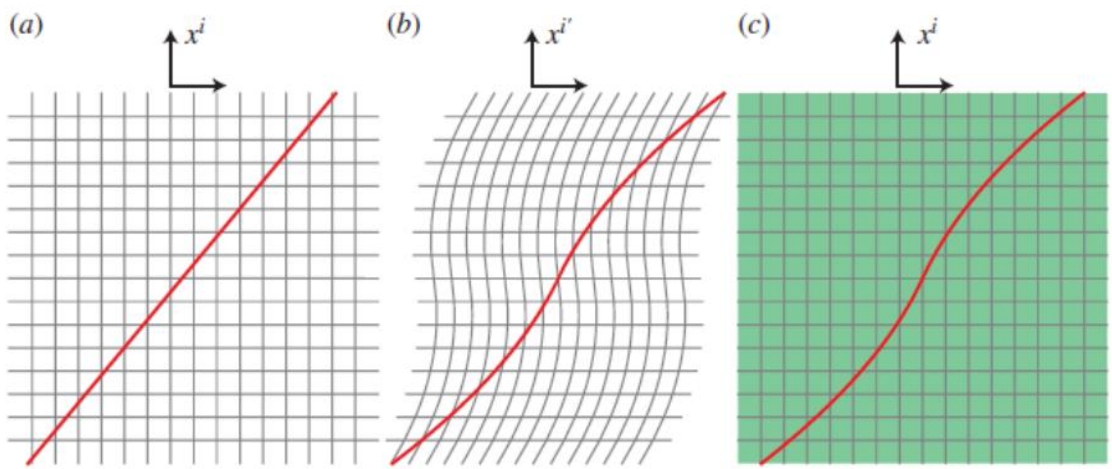
Validate

- Measure index of refraction
- Measure optical transparency

Project Description/<u>Scope</u>/Team

Goal ⇨ tailor electromagnetic features of a medium at will

- Spatially changing refractive index leads to changes in light propagation characteristics
  - E.g., Mirage
- Artificial media that have spatially changing optical properties can bend light in (almost) any manner
- Transformation optics ⇨ arbitrary anisotropic electromagnetic media



(a) **EM** in Cartesian coordinate system
(b) Same **EM** in deformed coordinate system $x' = f(x, y)$; $y'=y$
(c) **PH**, in which meta-material is implemented as of curved **EM** (b)

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$$\frac{\varepsilon_{x,x}}{\varepsilon_0 \varepsilon_b} = \frac{\mu_{x,x}}{\mu_0} = \frac{g'(y)h'(z)}{f'(x)}$$

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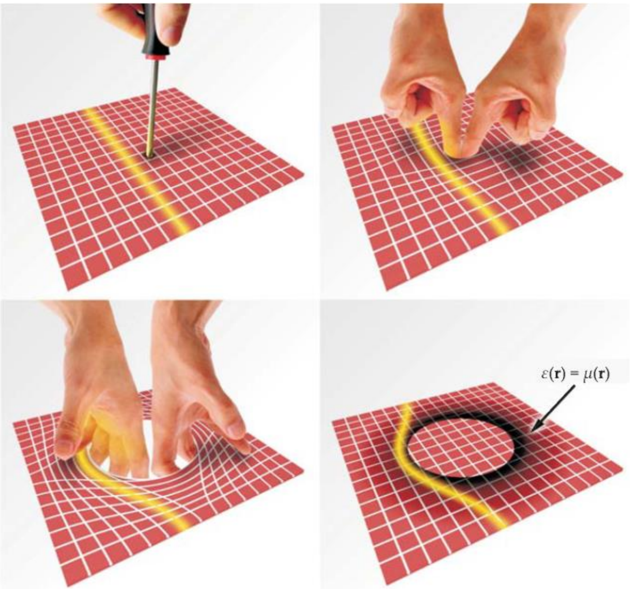
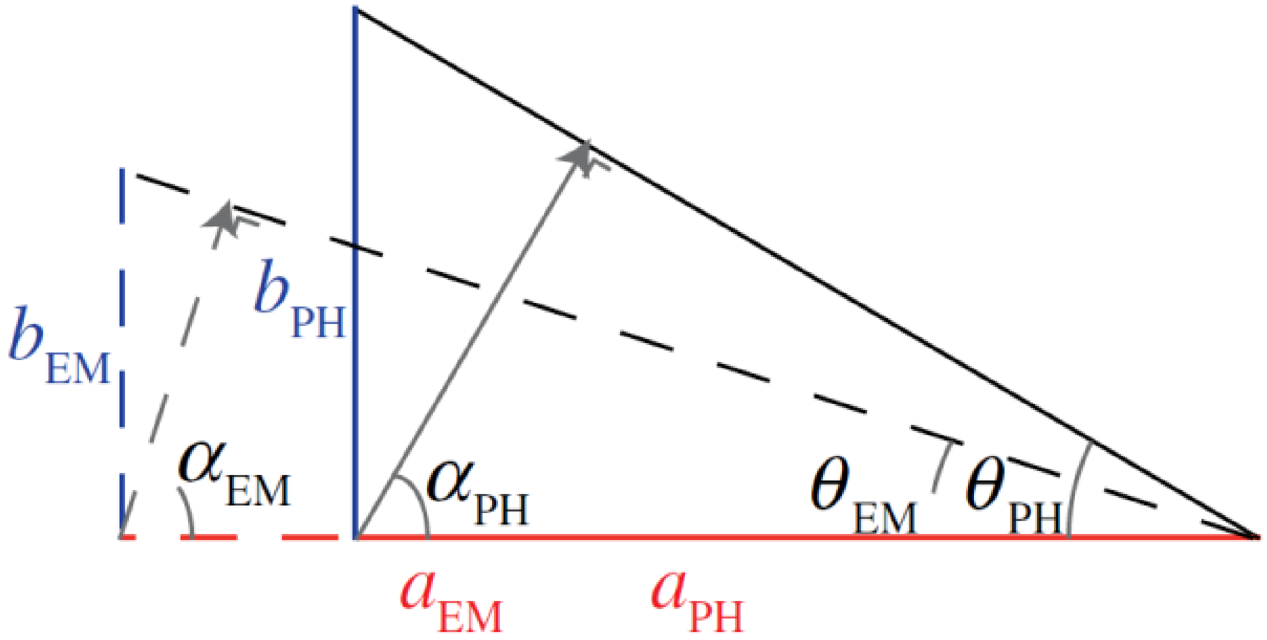


Project Description/Scope/Team

Cherenkov radiation obeys geometry of electromagnetic reality

Cherenkov cone can be manipulated with material parameters $\rightarrow$ coordinate transformations

Inhomogeneous Maxwell equations with plane monochromatic wave as solution yields dispersion relation $\rightarrow$ calculate Cherenkov angle in TOM



Project Description/Scope/Team

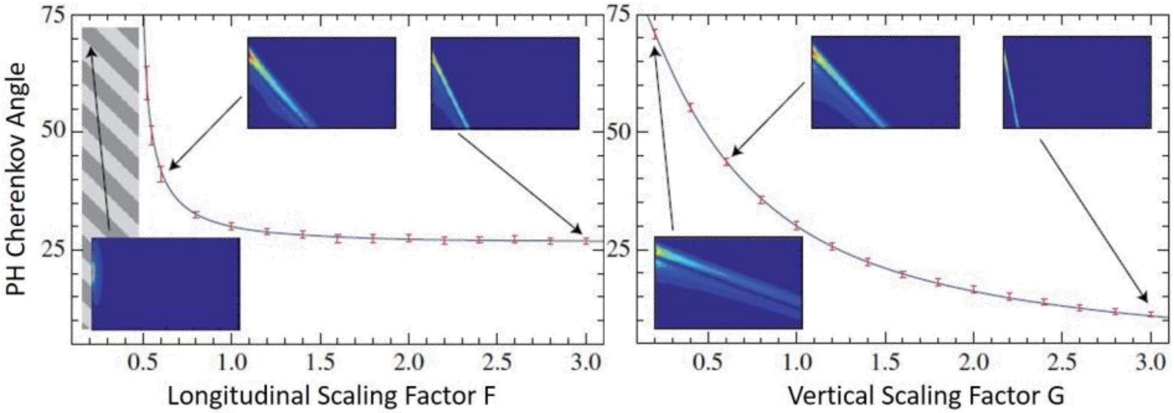
$$\tan(\alpha_{PH}) = \frac{k_y}{k_x} = \frac{G}{F}\frac{\sqrt{F^2\epsilon_b\omega^2/c^2 - k_x^2}}{k_x} = \frac{G}{F}\tan\left(\theta_{Ch,(Fn_b)}\right)$$

$\theta_{Ch,(Fn_b)}$: angle of Cherenkov radiation emitted in a medium with refractive index Fn_b

Compare to classical Cherenkov angle:

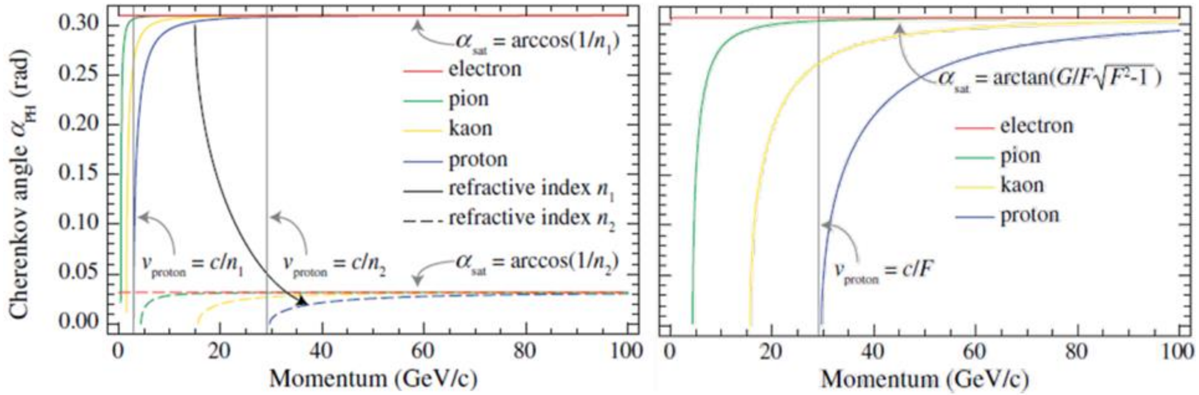
$$\theta_{Ch} = \arccos\left(\frac{1}{n\beta}\right) \text{ vs. } \theta_{Ch,n_b} = \arccos\left(\frac{1}{Fn_b\beta}\right)$$

Full-wave numerical simulations of Cherenkov radiation
$c/(n_b v) = 0.5$



$G = 1$ $F = 1$

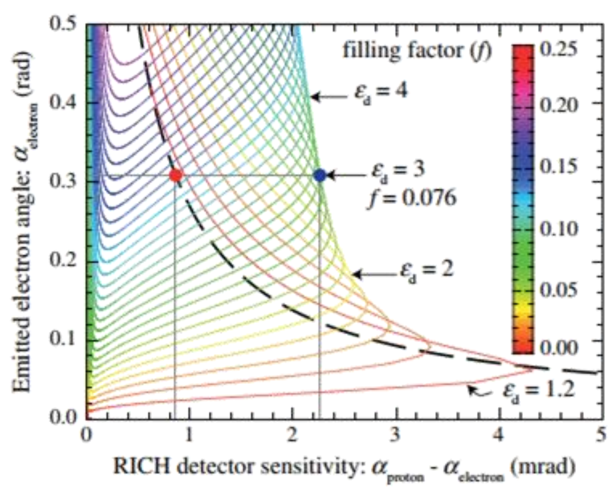
Project Description/Scope/Team

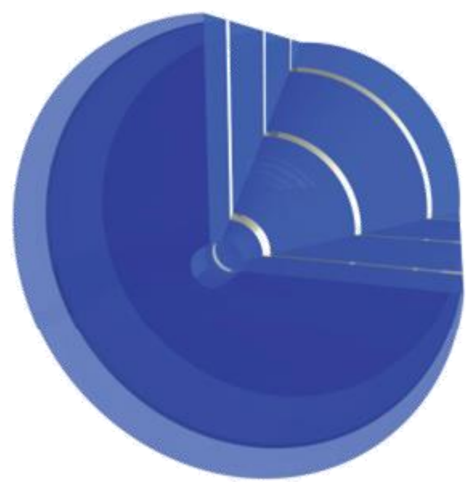


Aerogel vs CF_4

"Meta-CF_4"
$F = 1.0005 \quad G = 10$

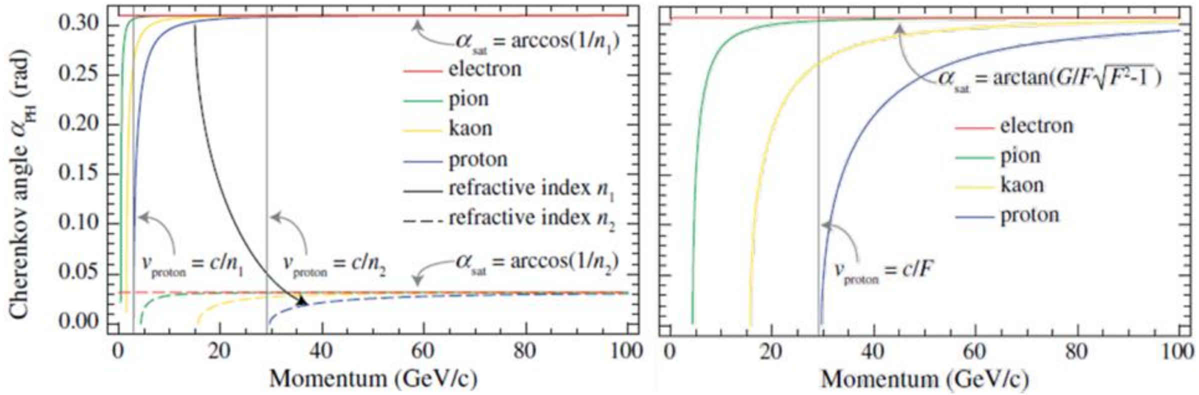
Large anisotropy required for transformation not readily available in naturally occurring materials but can be obtained from electromagnetic structured materials ⇨ array of thin metallic discs embedded in dielectric medium





Jefferson Lab

Project Description/Scope/Team



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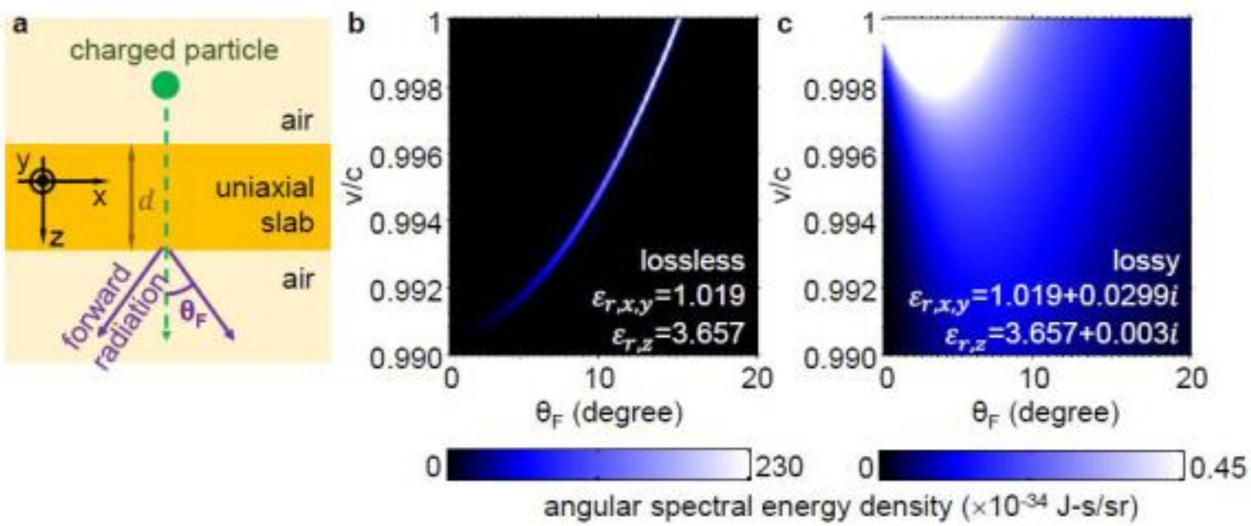
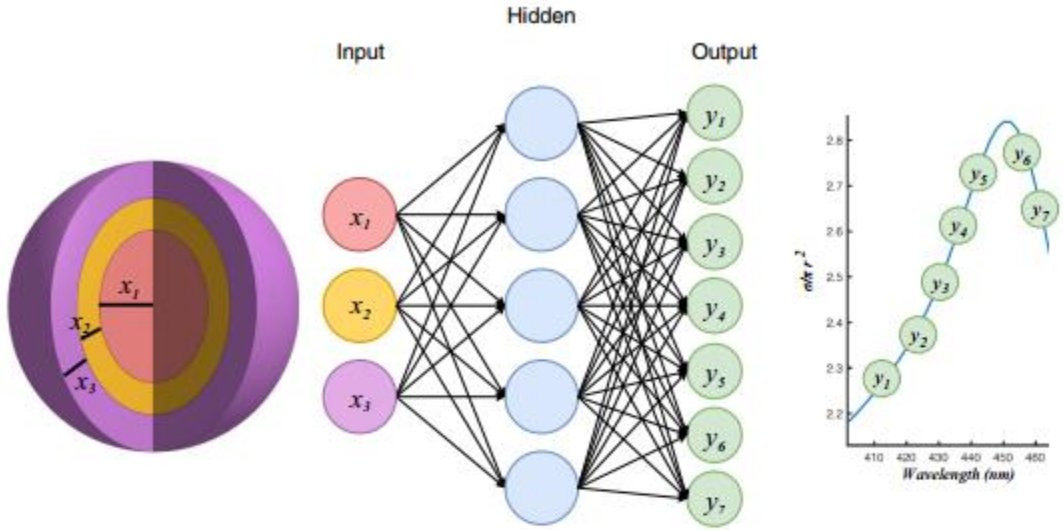


Project Description/Scope/Team

Goal ⇨ identify suitable materials

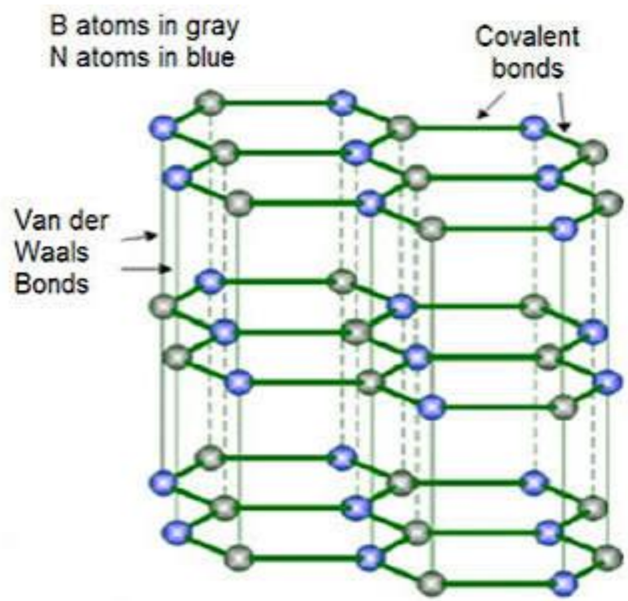
- Simulate optical properties ⇨ T-matrix $\begin{pmatrix} \mathbf{p} \\ \mathbf{q} \end{pmatrix} = \mathbf{T} \begin{pmatrix} \mathbf{a} \\ \mathbf{b} \end{pmatrix} = \begin{pmatrix} \mathbf{T}^{11} & \mathbf{T}^{12} \\ \mathbf{T}^{21} & \mathbf{T}^{22} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{a} \\ \mathbf{b} \end{pmatrix}$
- Gauge results ⇨ Finite Element Analysis (e.g., COMSOL)
- Train the ANN
- Run ANN
  - Forward prediction ⇨ outputs the complete optical responses given the geometric parameters
  - Inverse retrieval ⇨ outputs the geometric parameters from the required optical responses



Project Description/Scope/Team

Goal ⇨ synthesize materials with anisotropic ε_r

- Required characteristics ⇨ large n_r and low optical absorption
- Potential candidates ⇨ HfO_2, GaN, BN or h-BN
- Chosen candidate ⇨ h-BN
  - BNNT Inc. in Newport News empowers groundbreaking nanotechnology applications in R&D through its innovative production of the world's highest-quality Boron Nitride Nanotubes
  - BNNT Inc. will arrange layers of *bnnts* in different geometrical configurations
  - BNNT Inc. and proponents will determine the optical characteristics

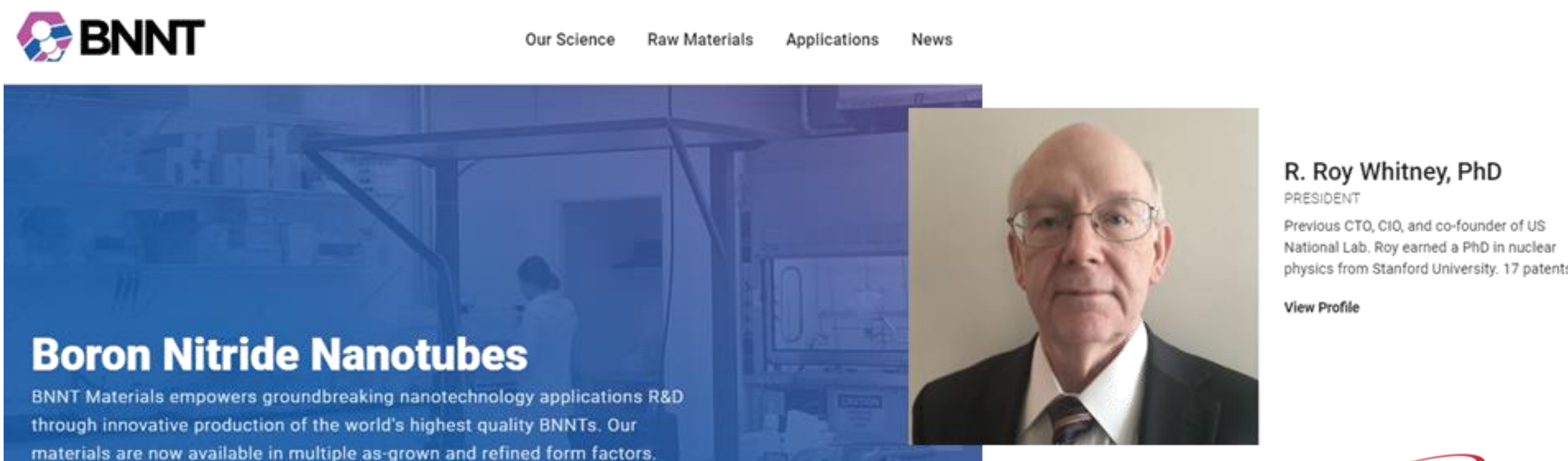


Project Description/Scope/Team

Team members

Team Member	Role	Project Contribution	Specific Aims
Klaus Dehmelt	PI	Guide the development of the ANN, support synthesizing new materials for RICH applications, oversee the project as PI	1 – 13
Carl Zorn	Co-I	Characterization using optical techniques	7, 9, 10, 13
TBD	Postdoc	Develop ANN, verify ANN, run ANN, support material synthesis, support material evaluation	1 – 7, 13

Commercial partner



Impact and Strategic Value to the Laboratory's Mission

- ***A positive outcome of the project's objectives would establish a spectacular instance in detector physics***

- ***A positive outcome of the project's objectives would place the laboratory in a favorable position regarding detector development and deployment for JLab, the EIC physics program, and beyond***

- ***A positive outcome of the project's objectives would expand the portfolio of applications***

Level of Innovation

- *Transformation optics is a well-established mathematical and physical concept*
- *Solutions for meta-materials have been proven – conceptually*
- *ANN exist for physical applications and is proven – conceptually*
- *Many proposed applications on meta-materials – on conceptual levels*
- *This proposal attempts to realize concepts and transform them into workable applications*

If realization is successful, it will provide a spectacular innovation in the field of nuclear/particle physics detector applications and beyond – textbooks have to be expanded (L. Greiner, K. Kleinknecht, R. K. Bock, C. Grupen, D. Green, etc.)

Deliverables – Timelines and Milestones

ANN

Table 1 Milestone tasks for ANN

#	Milestone Task	Time
1.	Verify the ANN codebase against its functionality	**Months 1 – 4**
2.	Develop T-matrix and COMSOL-FEA gauging strategy	**Months 5 – 9**
3.	Implement the T-matrix method and produce training samples	**Months 10 – 11**
4.	Train ANN	**Months 12 – 13**
5.	Test inverse design	**Months 14 – 15**
6.	Identify feasible materials	**Months 16 – 18**
7.	Produce feasible materials and test with BNNT	**Months 19 – 24**

BNNT

Table 2 Milestone tasks for BNNT

#	Milestone Task	Time
8.	Investigate synthesis strategies	**Months 1 – 6**
9.	Measure optical properties: transparency	**Months 7 – 8**
10.	Measure optical properties: index of refraction	**Months 9 – 10**
11.	Investigate asymmetries	**Months 11 – 12**
12.	Investigate synthesis based on ANN outcome	**Months 16 – 18**
13.	Produce feasible materials and test	**Months 19 – 24**

Budget and Budget Justification

Requested Budget for Effort by Investigator									
Name of Investigator	**Role (PI, Co-I, etc.)**	**FY25 Budget ($K)**	**FY25 Effort (% FTE)**	**FY26 Budget ($K)**	**FY26 Effort (% FTE)**			**Total Budget ($K)**	**Total Effort (%FTE)**
Klaus Dehmelt	PI	76.778	20.0	78.122	20.0			154.900	20.0
Carl Zorn	Co-I	19.195	5.0	19.530	5.0			38.725	5.0
	Subtotal for effort	95.973	25.0	97.652	25.0			193.625	25
Equipment	Non-capital								
	Capital								
Subcontracts	Postdoc/JLab	123.0	100	125.153	100			248.153	100
Materials/ Supplies	COMSOL	21.0						21.0	
	BNNT	35.0		65.0				100.0	
Travel		N/A		8.0				8.0	

Budget and Budget Justification

Name of Hire	Type of hire (strategic, staff, PD)	Position Description/Justification	Projected Cost ($K/FY)	Expected timeline
TBD	Postdoc	Development of software, test measurements materials, and prototypes	123.0/FY25 125.2/FY26	Jan.'25-Dec.'26

Name of Material	Description	Cost per FY	Total Cost
COMSOL FEA Package	Finite Element Software Package COMSOL Multiphysics COMSOL AC/DC module COMSOL RF Module COMSOL Wave Optics module	$14k/FY25 $7k/FY26	$21k
Material (Synthesis) BNNT	Materials as described in Table 2	$35k/FY25 $65k/FY26	$100k

Activity	Destination	Name of travelers	Estimated Cost
APS March Meeting 2026	Denver, CO	Postdoc	$2000
12th International Workshop on Ring Imaging Cherenkov Detectors 2026 (5 days)	(TBD)	Postdoc, PI	$6000

Potential Future Funding

- If the proposed work has a positive outcome ⇨ funding agencies like DOE and NSF will engage to fund further R&D
- Commercial partners, spin-offs, SBIR, …

Summary – Conclusions

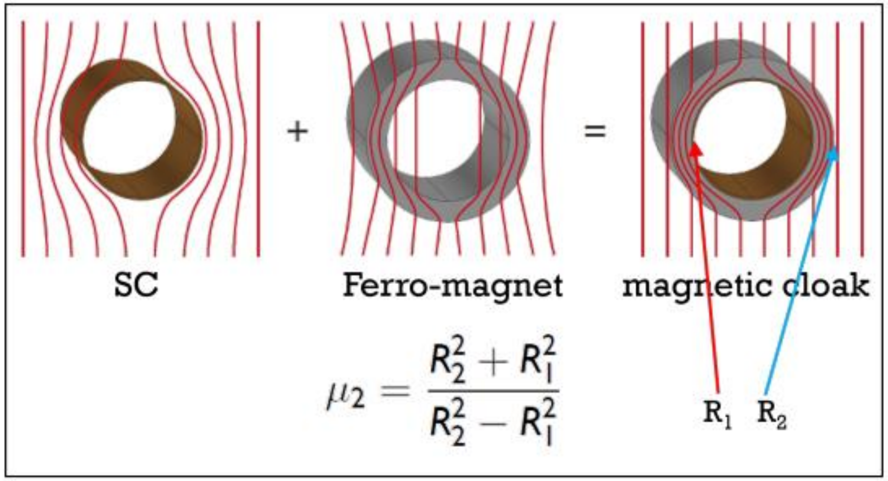
The target of this proposal is highly speculative and blue-sky research ⇨ but considerable amount of success!

Provided successful outcome:

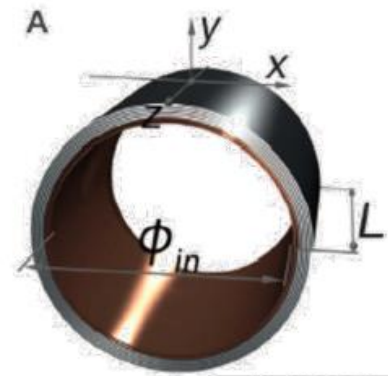
- Project description, scope, and team for this proposal are well-articulated and well-positioned
- Highest impact and strategic value to the Laboratory’s mission
- Highest level of innovation
- Realistic deliverables with corresponding timelines and milestones
- Realistic budget and its justification
- Large potential for future funding


BACK UP

Meta-material Application



Fedor Gömöry *et al.*, *Science* **335**, 1466 (2012), DOI: 10.1126/science.1218316

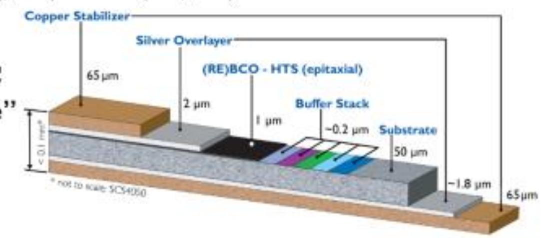


SC tape @ R_1: ReBCO (cuprate HT-SC)

FM-tape @ R_1 to R_2: $Fe_{18}Cr_9Ni$, $\mu_2 = 3.54$

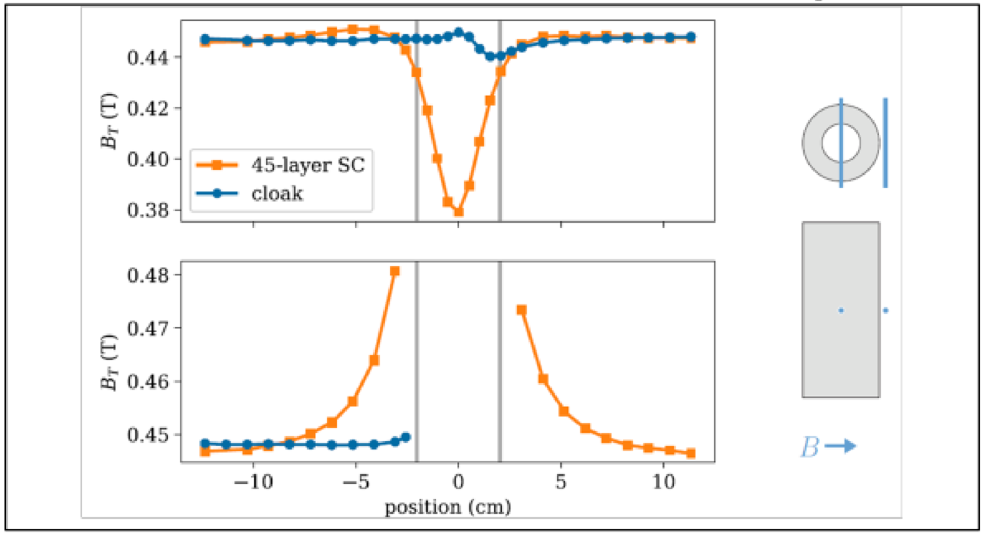
manufacturing FM with customized μ_r dependent on fractional mass f_m

manufacturing SC with ReBCO "tape"

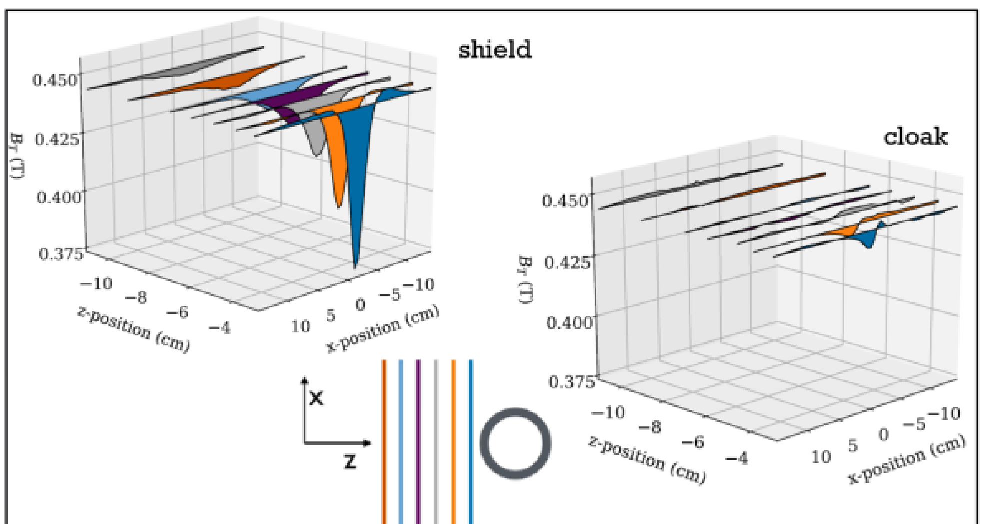


Meta-material Application

4.5 inches long -- 45-layer SC shield/cloak(μ_r=2.43)



μ_r effectively reduced due to higher fields



Meta-material Application

From

DOI: 10.1002/lpor.201700034

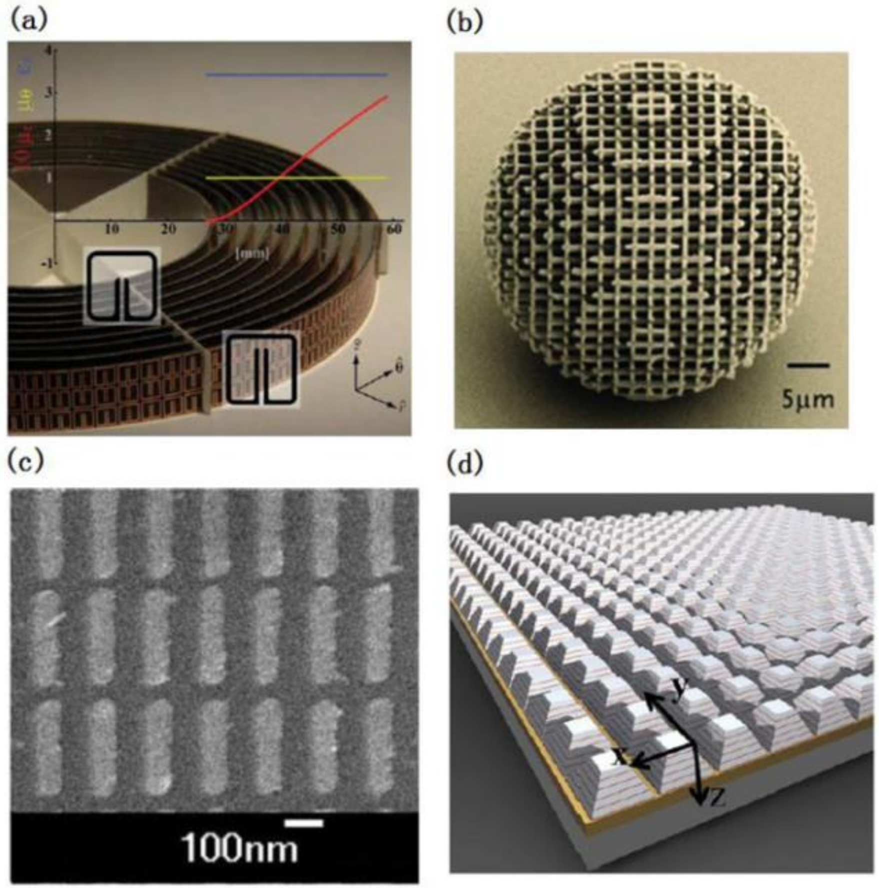


Figure 3. Various designs and applications of metamaterials. (a) Invisibility cloak in the microwave band (Reproduced with permission from Ref. [28]. Copyright (2006) Science). (b) 3D gradient control to realize the Luneburg lens at optical frequencies (Reproduced with permission from Ref. [129]. Copyright (2016) Laser Photon. Rev.). (c) Near-field subwavelength focusing (Reproduced with permission from Ref. [130]. Copyright (2009) Phys. Rev. A). (d) Deformable broadband absorber (Reproduced with permission from Ref. [131]. Copyright (2014) Laser Photon. Rev.).