R&D Activities at IDM-ESRF on High-Temperature Superconducting Insertion Devices

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Insertion Devices and Magnets Group
ESRF

10th Low Emittance Rings Workshop
8-10 October 2025

OUTLINE

I. Motivation

a. High-Field, Short Period undulators

II. High-Temperature Superconducting REBCO Technology

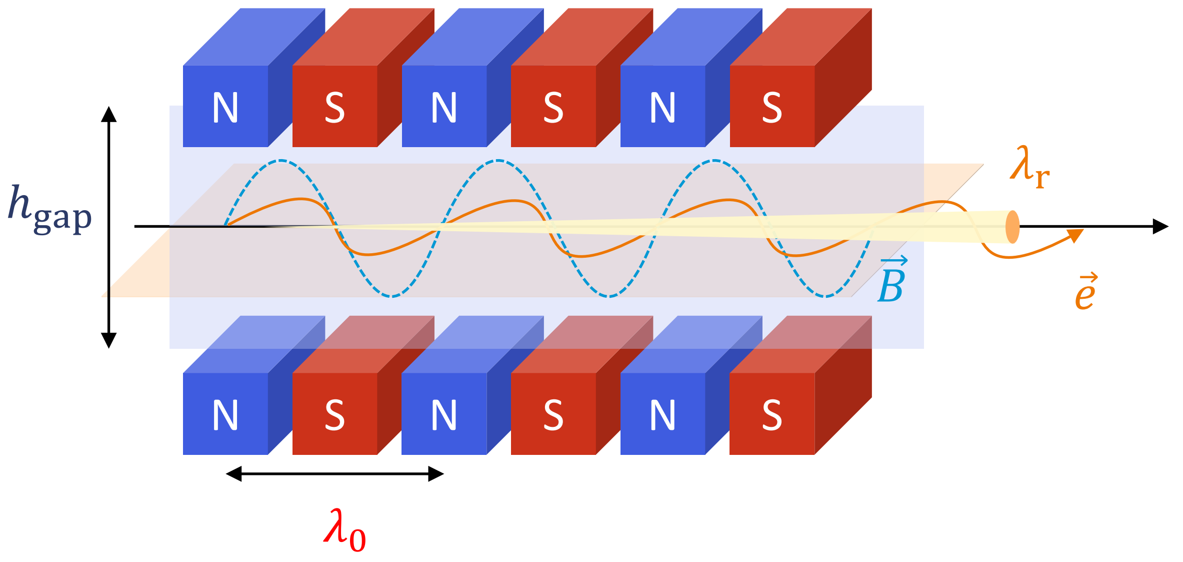
a. Potential
b. Limits

III. Superconducting Wiggler for the ESRF

a. Beamline 18 Upgrade
b. Wiggler Design
c. Numerical Results
d. What’s Next

Wigglers and Undulators

- Periodic magnetic structures in straight sections of storage rings
- Emission of intense, tunable radiation by wiggling relativistic electrons
- **Magnetic field strength**, **period length**, **field quality**.
- Interface between machine and users



Planar undulator as light source

Deflection parameter:

$$K = \frac{e}{2\pi mc} B \lambda_0$$

Radiation wavelength (on-axis):

$$\lambda_{r,1} = \frac{1}{n} \frac{\lambda_0}{2\gamma^2} \left(1 + \frac{K(B, \lambda_0)^2}{2} \right)$$

Radiated energy:

$$E_n = n \frac{hc}{\lambda_{r,1}}$$

Example ESRF CPMU:
λ_0 = 18 mm
K = 1.81
$\gamma \approx 11742$
$E_1 \approx 6$ keV

Potential for Physics

Higher Brilliance: Better resolution, faster data collection, smaller samples

Higher harmonics: More science, same machine (same science, cheaper machine)

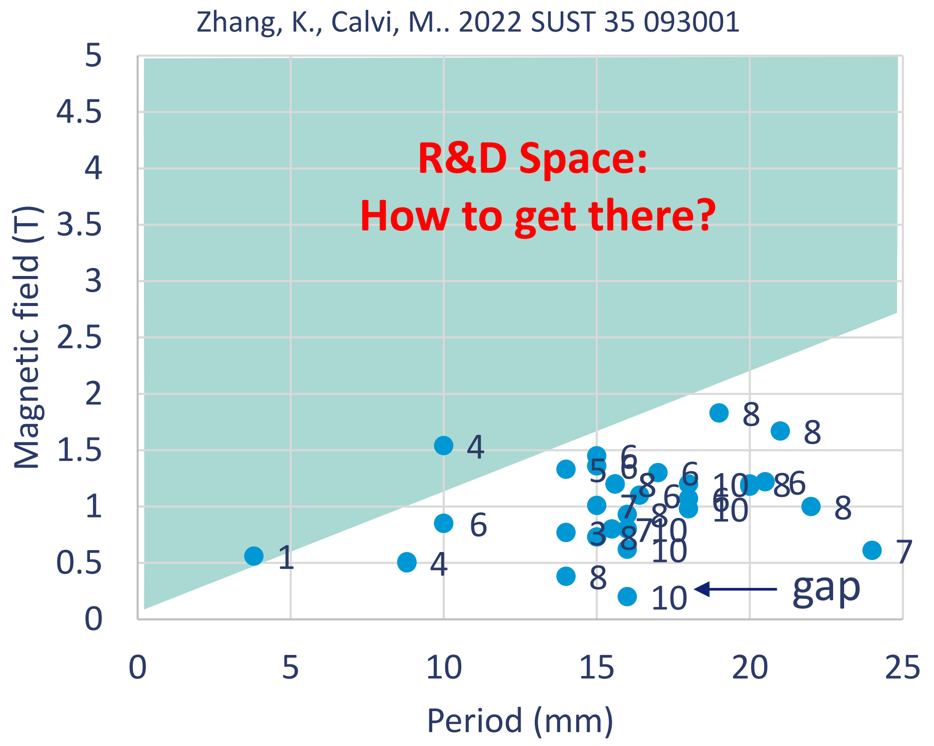
Compactness: More space in straight sections

Engineering perspective

Increase radiation power per length
-> more periods -> **Shorter period λ_0**

Increase photon flux
-> keep $K \propto B\lambda_0$ -> **Stronger magnetic field B**

… Increase Power Density !



Planar undulators
(various technologies)

Conventional Technologies

Magnetic materials:

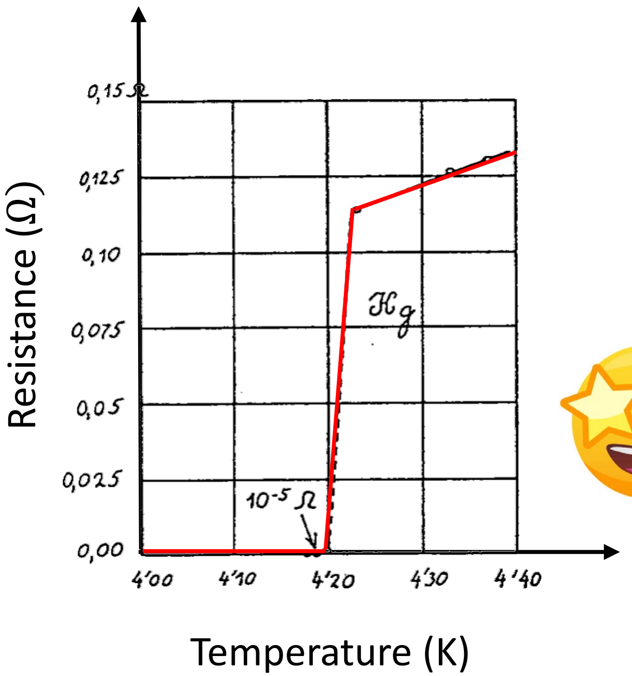
- PMUs limited in field at short periods.
- CPMUs do better, but still constrained.

Electromagnets:

- Doomed by Joule losses ($B \propto I$, but $P_{Joule} \propto I^2$)
- Limited power density due to heating

Superconductors

- Ohm's Law and **Joule losses** are **abolished!**
- Compact design, high power density



H. Kamerlingh-Onnes (1911):

The **experiment** left no doubt that the **resistance disappeared.** […]
Thus, the mercury at 4.2K has entered […] the **state of superconductivity.**

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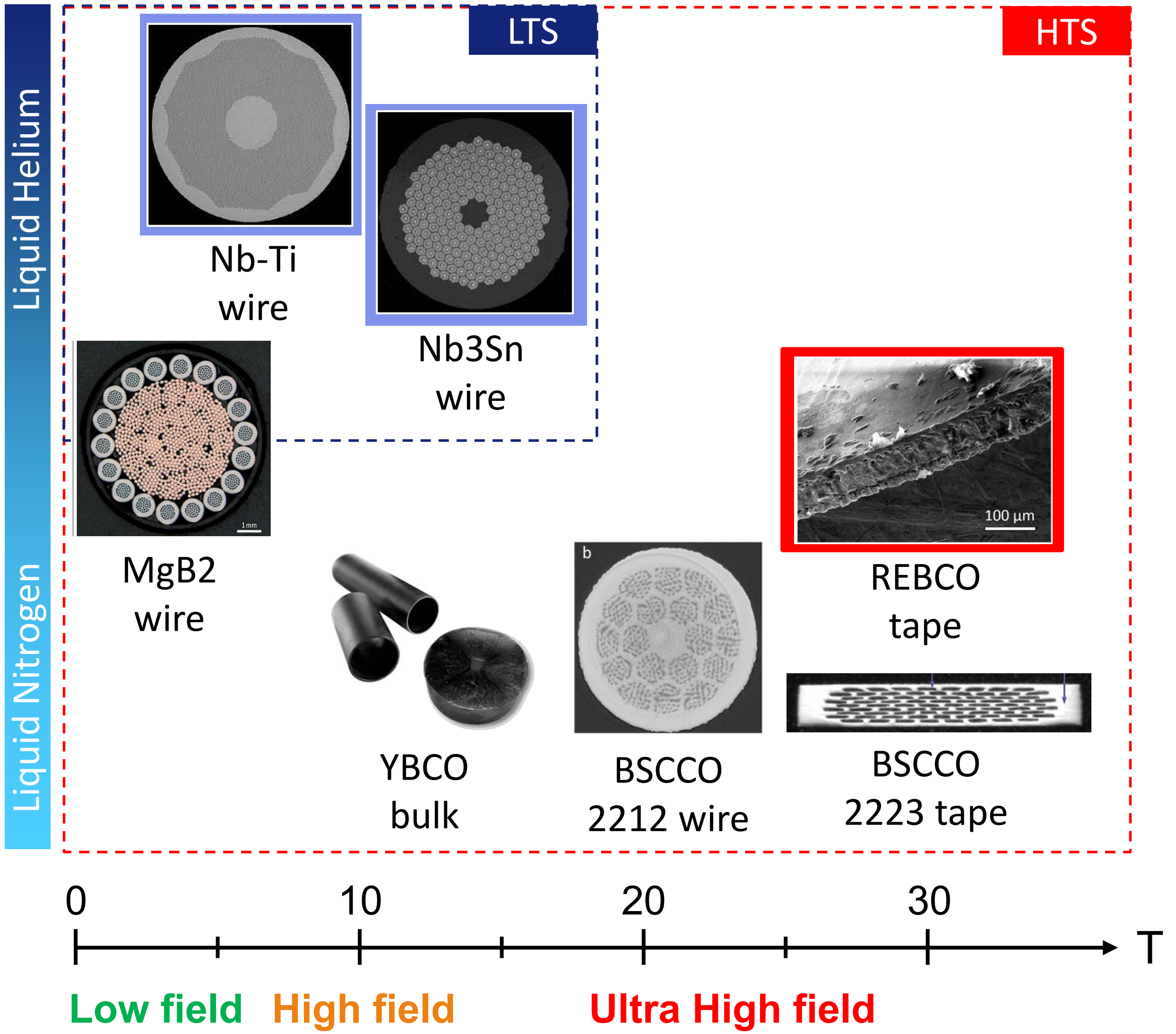
Considerations (some)

Physics:
Temperature, magnetic field, current density, mechanical forces, radiation hardness…

Coil design:
Shape, number of turns, layers and windings, joints, terminals …

Complexity:
Power supply, vacuum system, cryogenic system, diagnostics …

Technology:
Quality, characterization, data availability, reproducibility, **quantity at industrial scale**, supply chain resilience, price …



I. Motivation

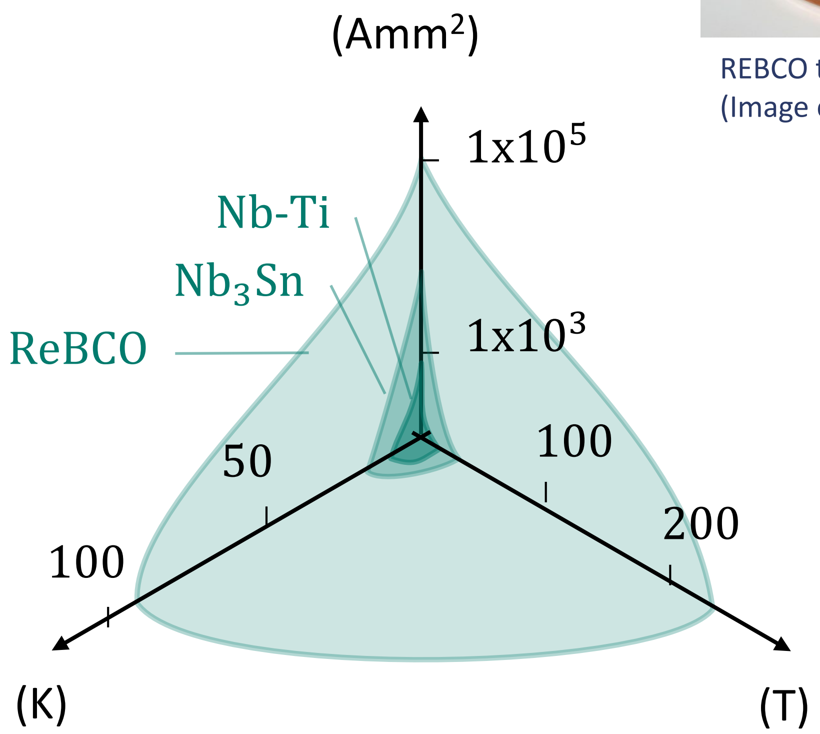
II. **High-Temperature Superconducting REBCO Technology**

III. Superconducting Wiggler for the ESRF

Materials superconducting above 77 K

Superconducting state below the **critical surface**, otherwise **quench**

REBCO tapes.
(Image credit: MetOx)



Critical surface (temperature, magnetic field, current density) for various superconductors.

HTS-REBCO tapes

Copper oxides (CuO_2) as thin films doped with rare earths, embedded in tapes.

- Record-high critical current density
- Critical temperature **93K** (Nb-Ti: 9.2K)
- Critical field **240T** (Nb-Ti: 14.5T)
- Anisotropic behavior (max. current density for B ∥ to tape wide surface)

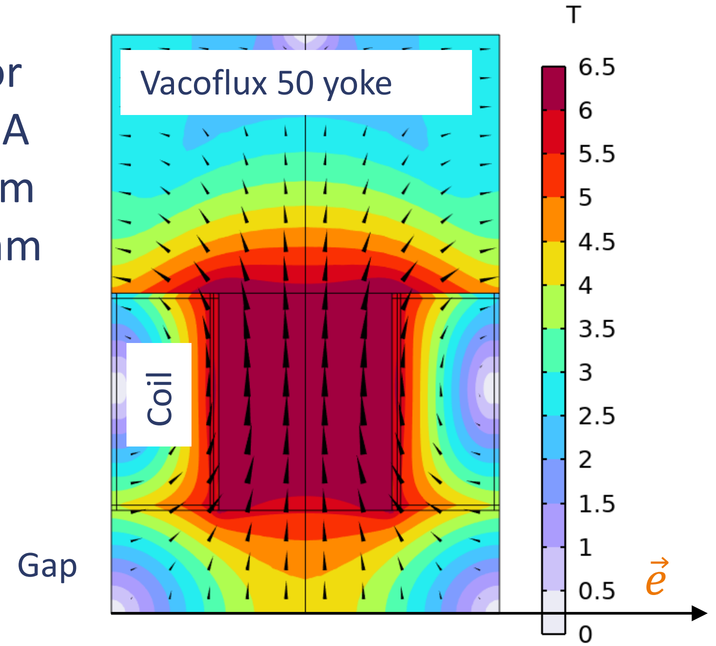
HTS performance > x10 than LTS !

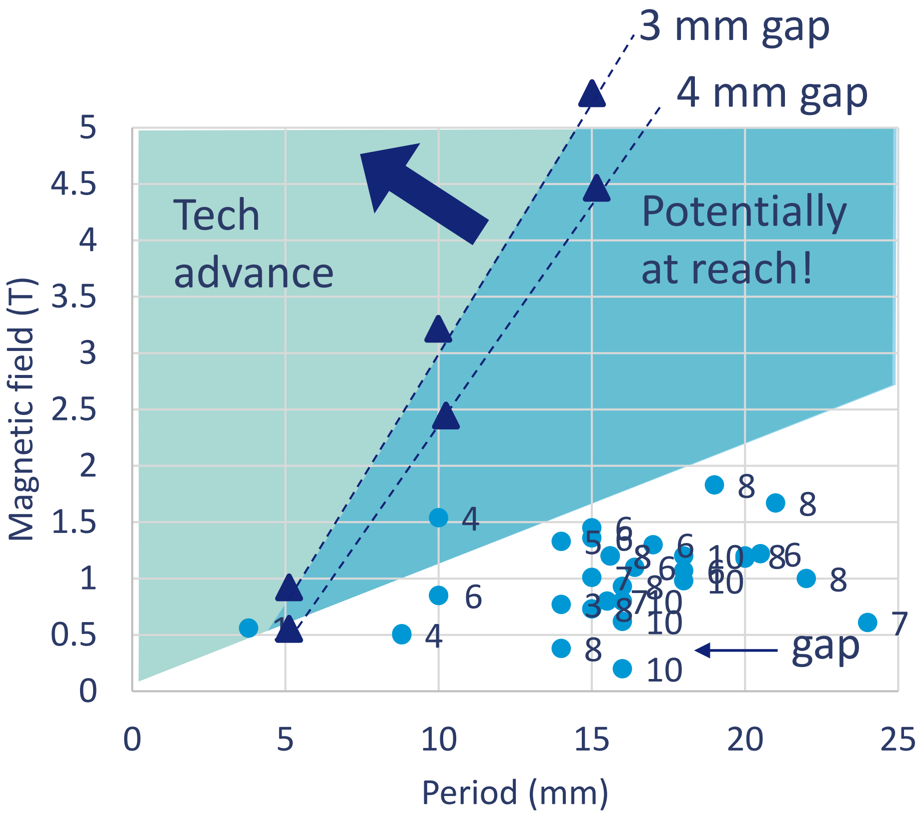
Magnetostatic Simulations (*)

(*) see also S. Richter's presentation at LER 2024
https://indico.cern.ch/event/1326603/contributions/5773995/

- Simplified 2D geometry
- Fusion grade, 65 um REBCO tape https://www.faradaygroup.com/en/product/
- Operations at 4.5 K, 80 % critical current

Results for
Is = 1000 A
λ_0 = 15 mm
h_{gap} = 4mm





Expected performance is unmatched !

Quench

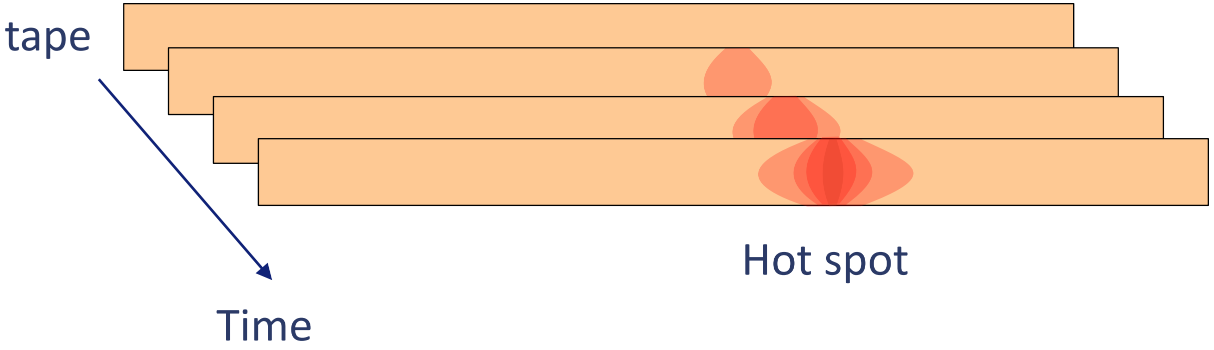
Local transition from superconducting to normal conducting state

Stored magnetic energy → **heat** in the superconductor

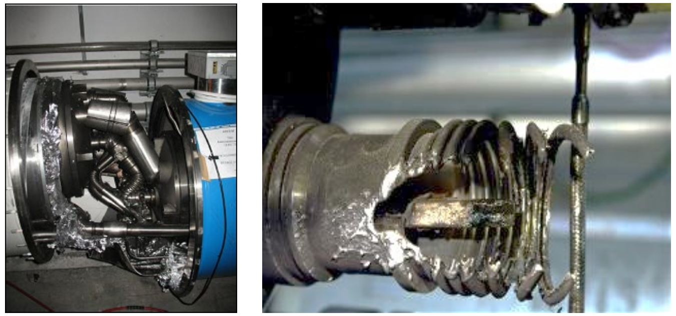
Possible **degradation** due to **local stress** and **thermal runaway**

REBCO tapes:

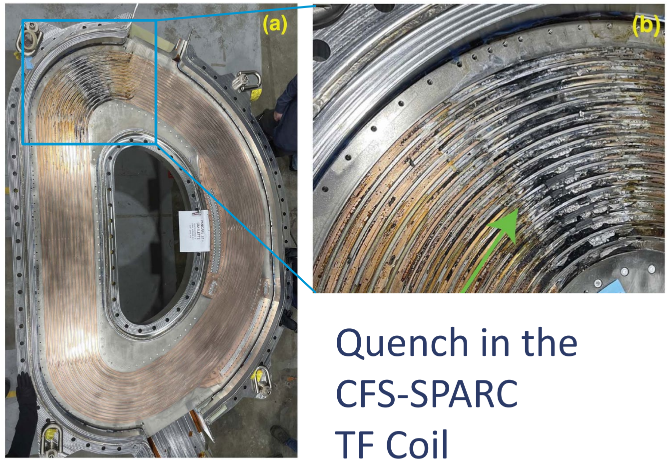
- **High** energy density
- **Slow** quench propagation (high T_c)
  → **difficult** quench detection → Potential damage



Mitigate consequences of quench !



LHC accident (2008)



Quench in the CFS-SPARC TF Coil

LaBombard IEEE-ASC 2024. https://snf.ieeecsc.org/files/ieeecsc/slides/LaBombard%20presentation.pdf

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TECHNOLOGICAL LIMITS OF REBCO TAPES (2/3)

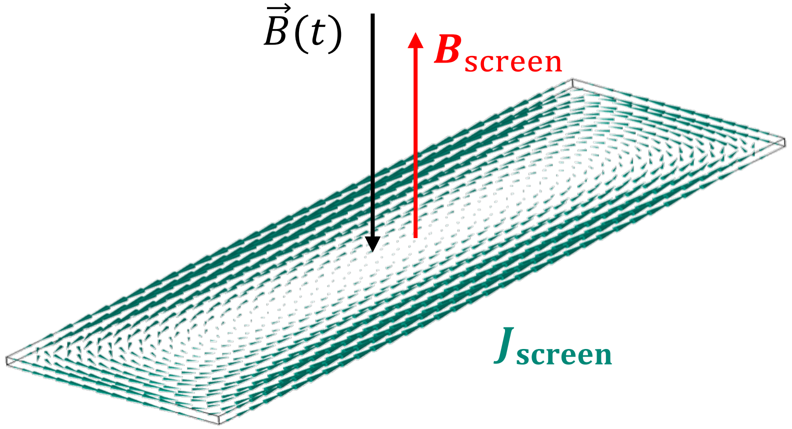
Magnetization

Changing magnetic field $B(\mathrm{T})$ (e.g. powering)

Induced electric field in the tape → eddy currents $\boldsymbol{J}_{\mathbf{screen}}$

$\rho \to 0$, therefore $\tau_{\mathrm{eddy}} \to +\infty$

→ Persistent magnetization $\boldsymbol{B}_{\mathrm{screen}}$, screening currents



Remarks

$\boldsymbol{B}_{\mathrm{screen}}$ undesired → potential **degradation** of **magnetic field quality**

$\boldsymbol{J}_{\mathbf{screen}}$ more significant at low transport current, and in wide tapes

Design nontrivial: extreme nonlinearity ($\rho \to 0$!), uncertainty in material properties

Prevent degradation of magnetic field quality !

Mechanical

Manufacturing: variety of thickness, deposition techniques, buffer layers…

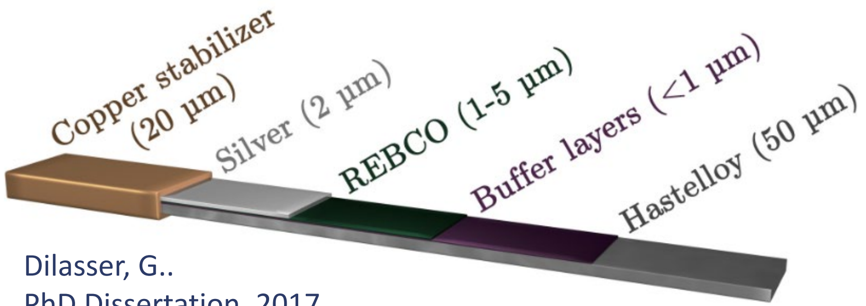
Tape characterization: low temperature, intense current and magnetic field

Brittle HTS layer: HTS properties degraded long before substrate mechanical failure

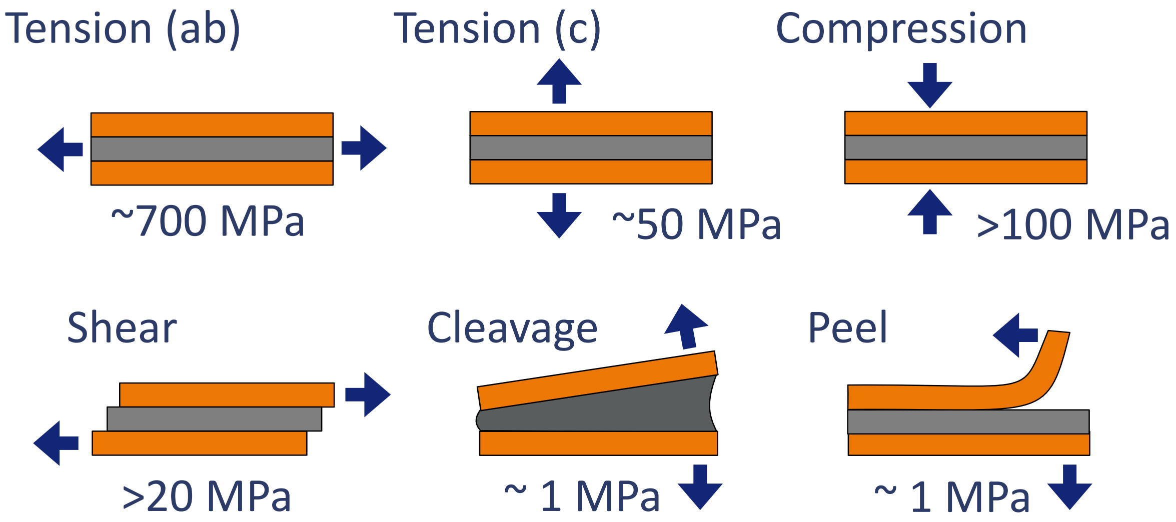
Bending limits: cracks if radius limits exceeded

Delamination: shear, cleave, peel forces from handling or coil winding

Lorentz forces: possible degradation from screening currents in high magnetic fields



Dilasser, G..
PhD Dissertation, 2017



Hideaki M., Yoshinori Y. IEEE 2014 4602412.

Magnet performance limited by mechanical degradation of HTS properties

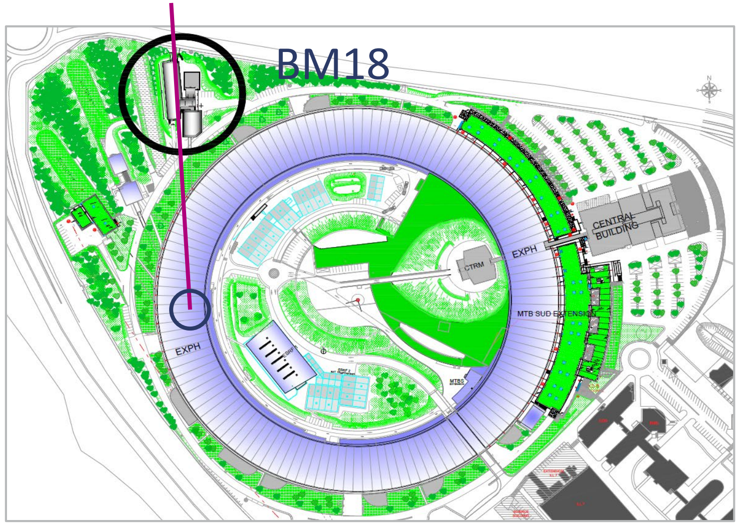
I. Motivation

II. High-Temperature Superconducting REBCO Technology

III. Superconducting Wiggler for the ESRF

Key features

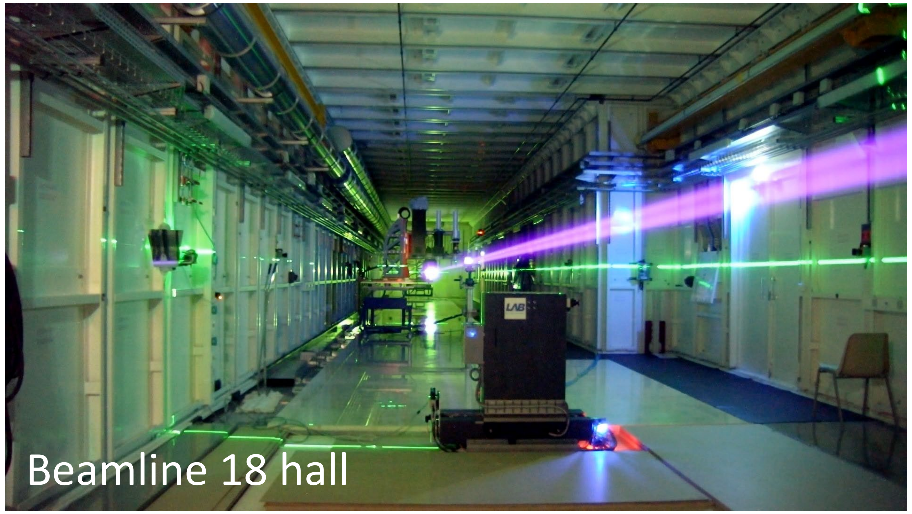
- High-energy X-rays for dense, thick materials
- Hierarchical tomography, radiography, diffraction
- Large field of view for large samples (e.g. industrial components)
- Operando and in situ capabilities for real-world test conditions



ESRF storage ring

Upgrade Needs

- Larger, more homogeneous radiation pattern
- **Field tunability** for reaching low energies
- Enhanced spectral quality



Beamline 18 hall

Images courtesy of P. Tafforeau

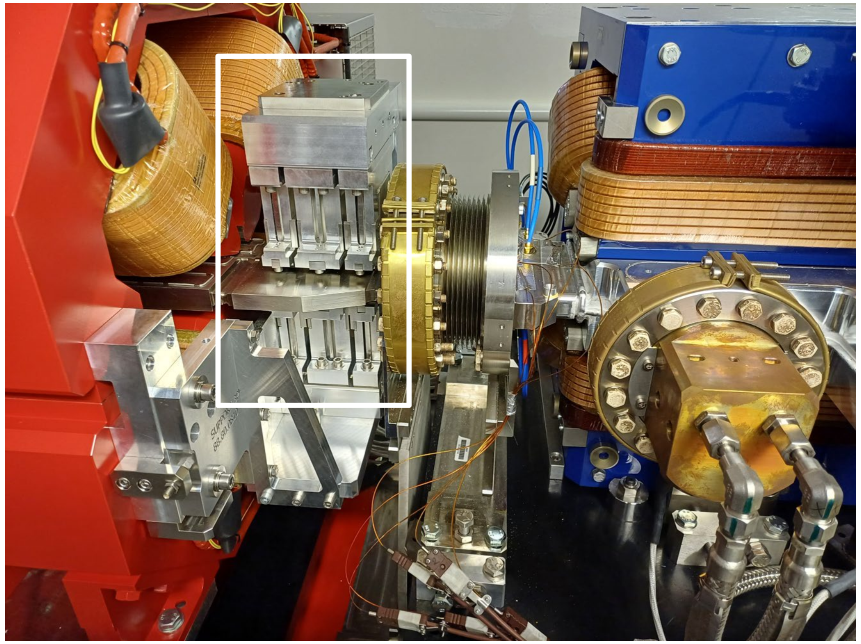
Permanent-magnet, 3-pole wiggler

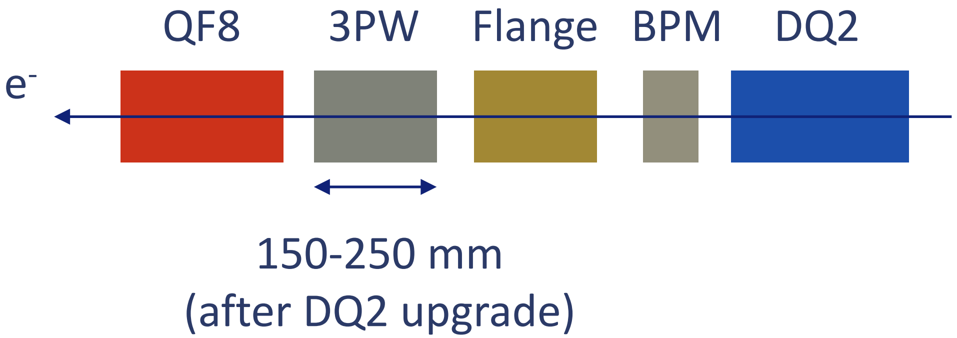
- Feasible… at fixed magnetic field
- Limited space for motorized frame

Compact, HTS, 3-pole wiggler

- Opportunity for technology development
- Development of design and manufacturing know-how

BM18 upgrade as **platform**
to develop HTS technology at the ESRF
towards short-period, HTS undulators





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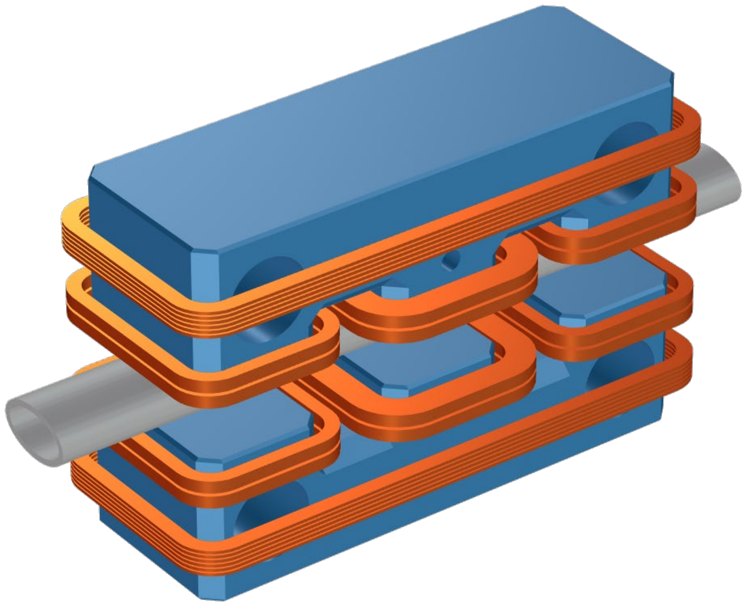
Low-risk, cost-effective HTS application

Design choices:

- Iron-dominated electromagnet (Co-Fe-V) of 200 x 90 x 120 mm
- Operations at 70A, 1.58T @ 65K (option for 1T @ 77K)
- Vacuum separated from storage ring (20 mm gap)
- Planar, double-pancake windings
- No-insulation windings (quench tolerance)
- High quench margin (~ 35%)
- Correction coil for residual errors



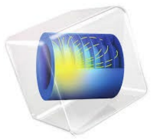
3D simplified rendering of the wiggler assembly

Simple, Robust, Feasible

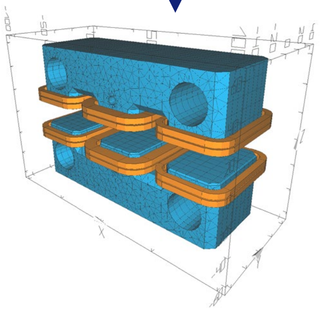
Iron yoke shape optimized for minimizing field integrals

Optimization loop :

INIT → Model parameters (JSON) → Model assembly → Stochastic optimization → Coil load-line verification → END

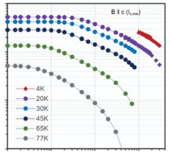


RADIA code [1]
CPython C API [2]



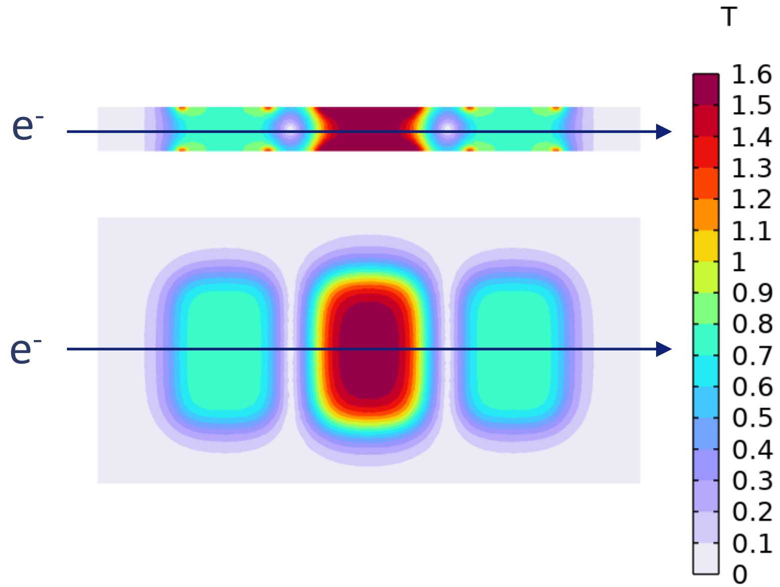
CPU CPU … CPU

Multiprocessing on ESRF HPC cluster

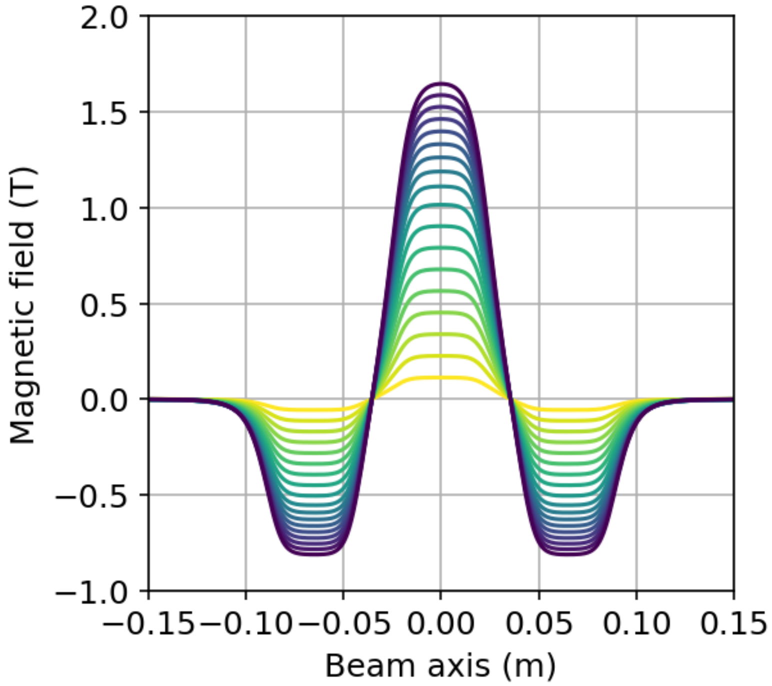


Critical current measurement [3]

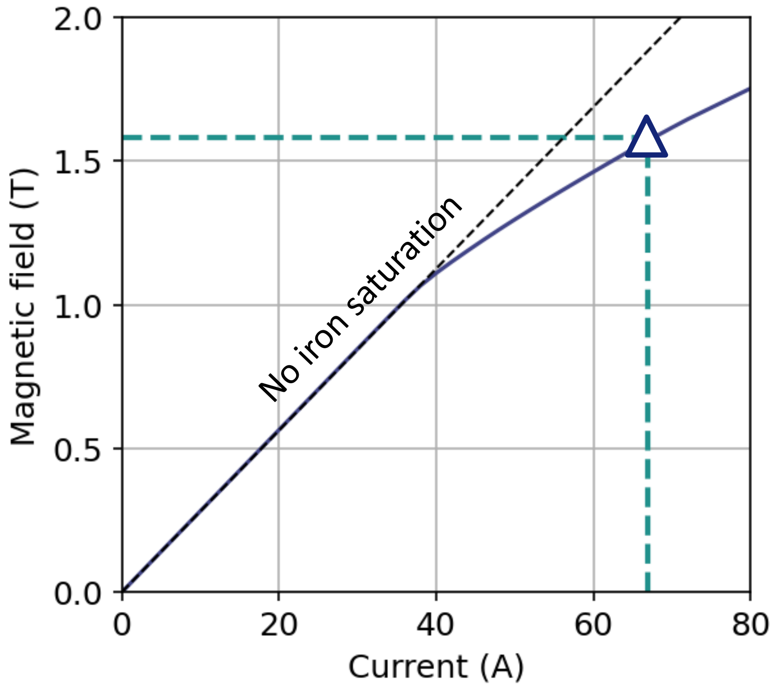
(1) https://github.com/ochubar/Radia
(2) https://gitlab.esrf.fr/radia-esrf/radia-python
(3) https://htsdb.wimbush.eu/dataset/25893079



Transversal (top) and planar (bottom) magnetic flux density in the gap



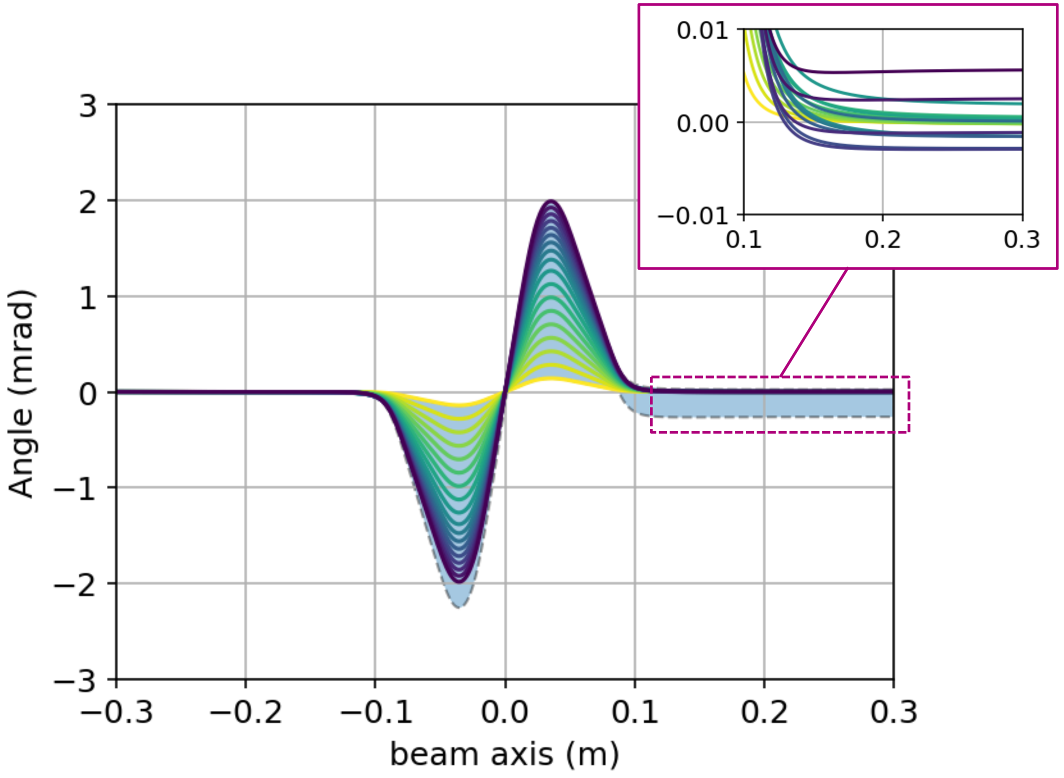
Axial magnetic flux density



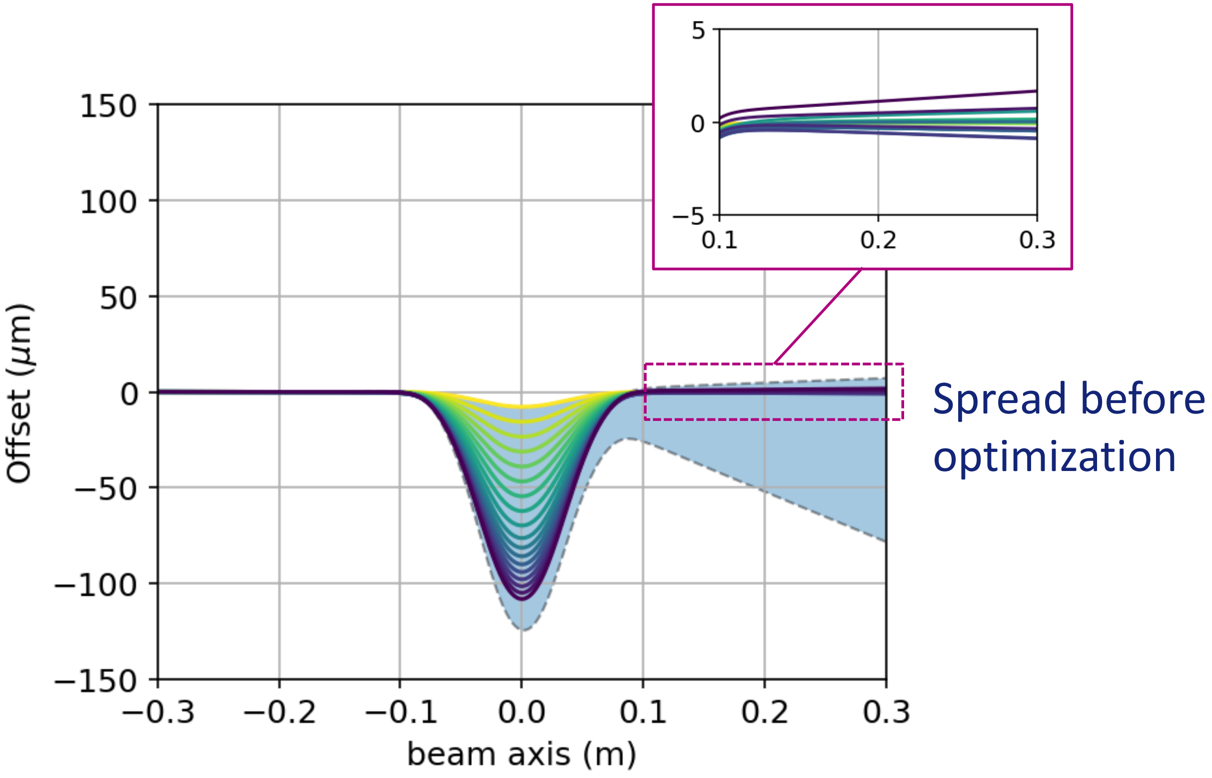
Magnet load line

Magnetic field within specs

RESULTS: MAGNETIC FIELD INTEGRALS



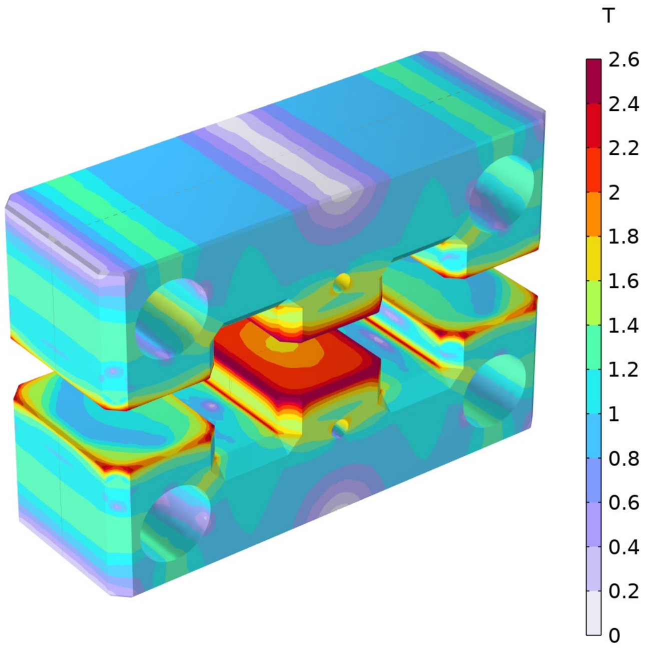
Beam angle, in mrad
($\propto 1^{st}$ field integral)



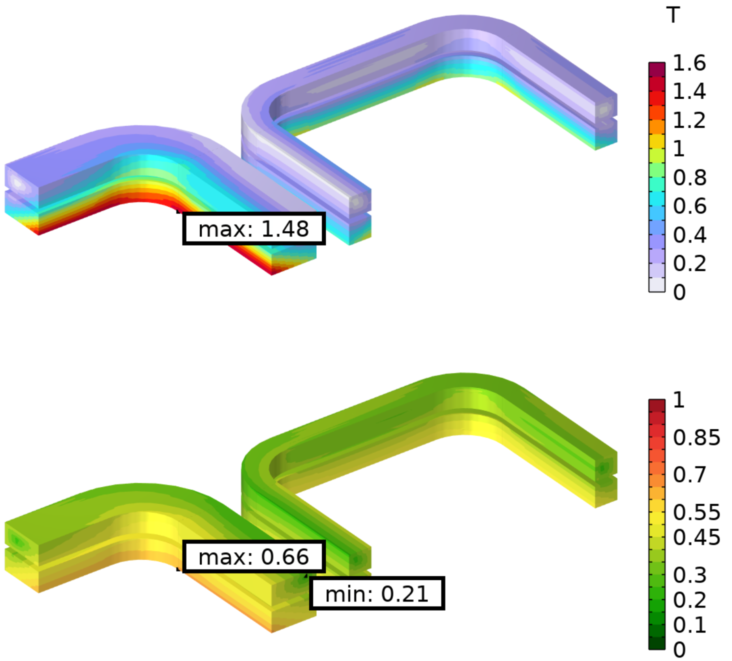
Beam offset, in μm
($\propto 2^{nd}$ field integral)

First and second field integrals corrected

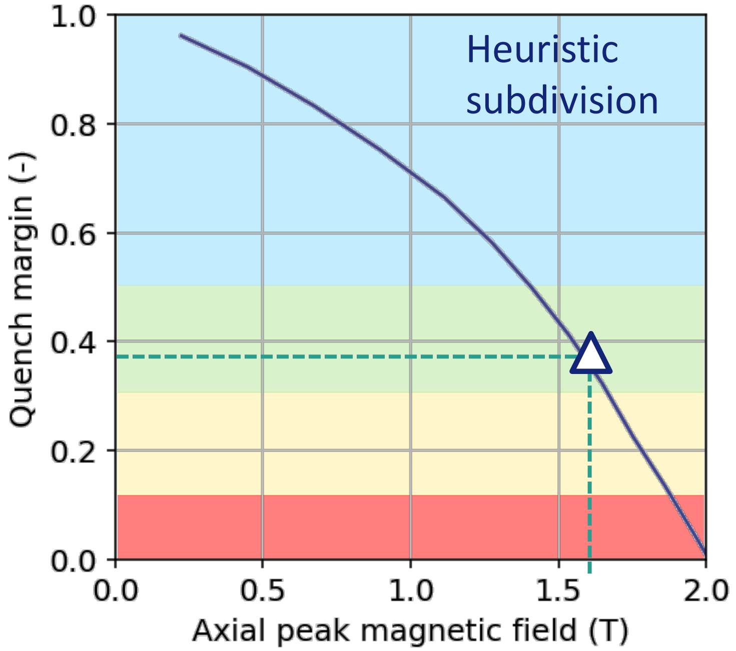
Results at temperature of 65 K



Magnetic flux density
in the iron yoke



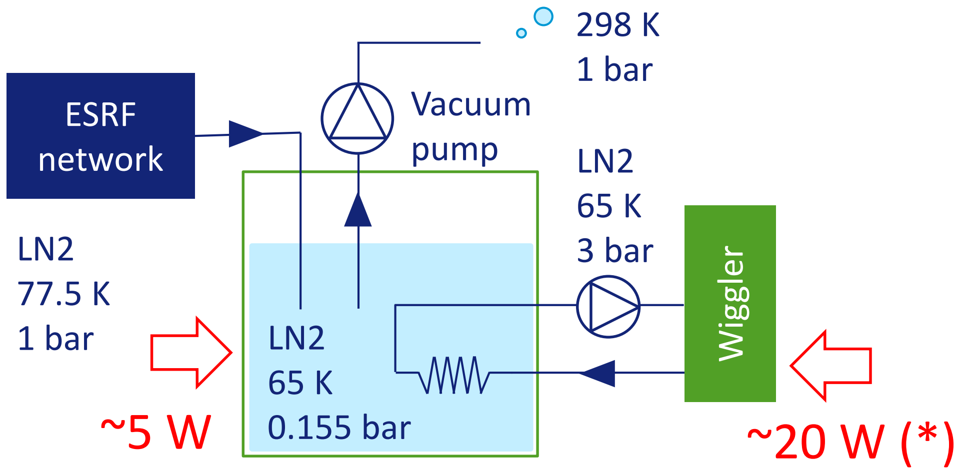
Magnetic flux density (top)
and coil load line (bottom)



Critical current (top) and
quench margin (bottom)

~ 65% of load line for operations at 65K

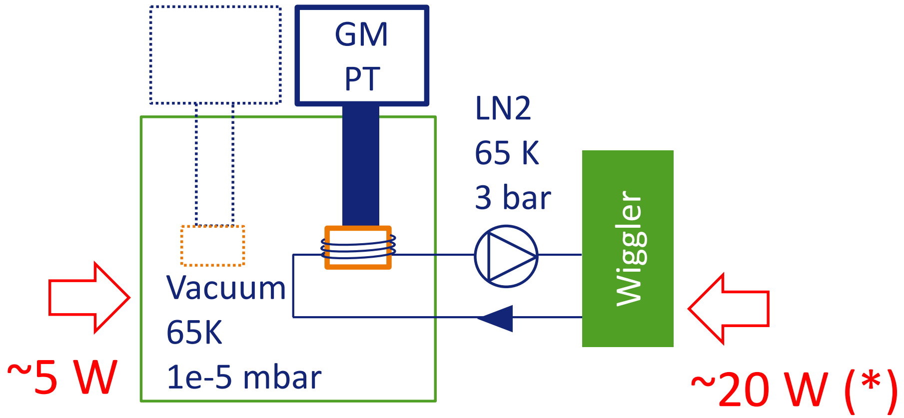
Vacuum Pumping on LN2 bath



- Simple (CPMUs experience)
- Nitrogen consumption
- “Fixed” minimum temperature (nitrogen freezing)

Cryocooler (Gifford / Pulse-tube)

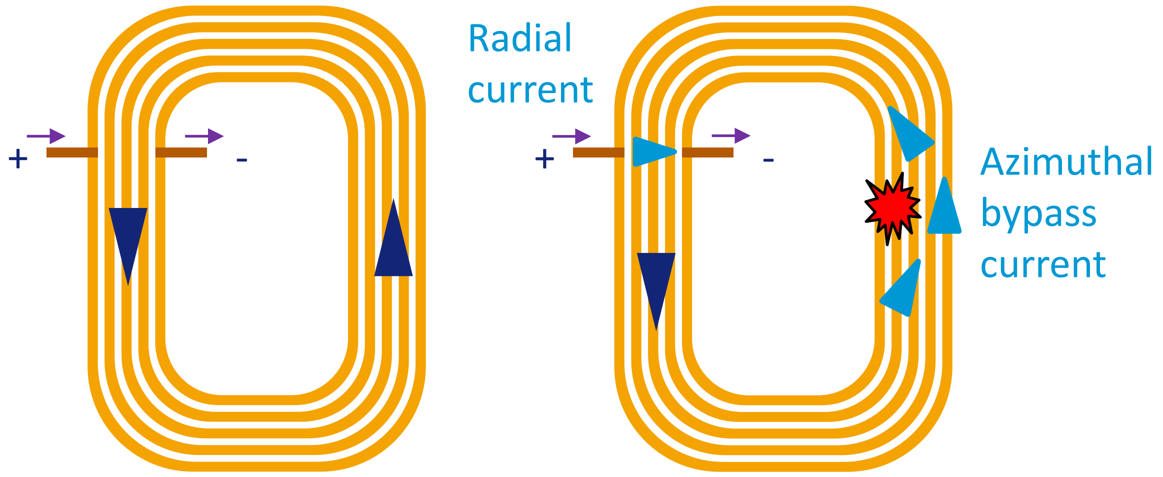
(*) excl. beam losses



- Complex
- No gas consumption
- Temperature regulation
- Cryo-head possibly integrated in wiggler cryostat + conduction cooling, eliminating transfer line

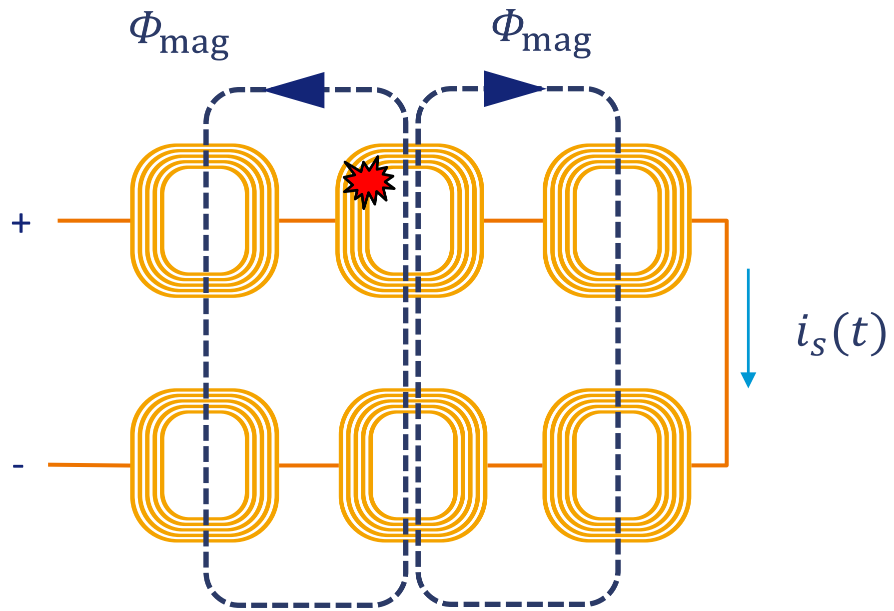
No-Insulation Coils

- Low turn-to-turn resistivity
- Azimuthal and radial current redistribution during a quench
- Effective bypass of the “hot” zone, reducing hot-spot temperature



Superconducting (left) and quenched (right)winding

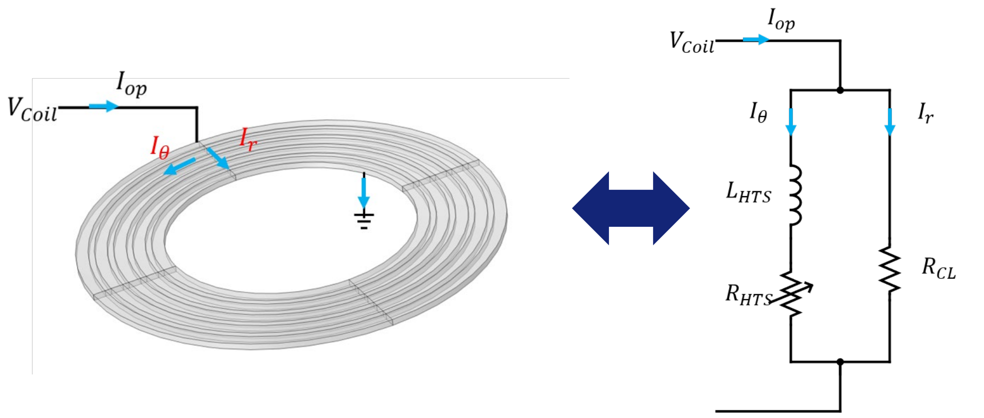
Magnetic field seen by the beam?



Numerical problem:

- multi-physics (magnetic, electric, thermal..)
- multi scale ($l_q \sim \mu m$, $l_{coil} \sim m$)
- multi-rate ($\tau_q \sim \mu s$, $\tau_{coil} \sim s$)
- … and nonlinear!

Topo- and Typo-logical Equations



$$\mathbf{A}^{\mathrm{T}}\mathbf{v} = \mathbf{0} \qquad \mathbf{Ai} = \mathbf{0} \qquad \mathbf{v}_{\mathrm{R}} = \mathbf{Ri}_{\mathrm{R}} \qquad \mathbf{v}_{\mathrm{L}} = \mathbf{L}\frac{\mathrm{d}}{\mathrm{dt}}\mathbf{i}_{\mathrm{L}}$$

L >> R, R → 0.
Possible non-physical oscillations and/or numerical artifacts

MEMEP Idea

Work by Zhishu Qiu
zhishu.qiu@esrf.fr

- Keep KCL
- Constrain KVL with a Minimum Electromagnetic Entropy Production (MEMEP) criterion $\mathcal{M}$:

MEMEP constraint :

$$\min_I \mathcal{M} = \mathbf{Ri}_{\mathrm{R}}\mathbf{i}_{\mathrm{R}}^{\mathrm{T}} + \alpha\frac{1}{2}\mathbf{Mi}_{\mathrm{L}}\mathbf{i}_{\mathrm{L}}^{\mathrm{T}}$$

$$\mathrm{A}^{\mathrm{T}}\mathrm{v} = \beta(\mathrm{i}_{\mathcal{M}} - \mathrm{i})$$

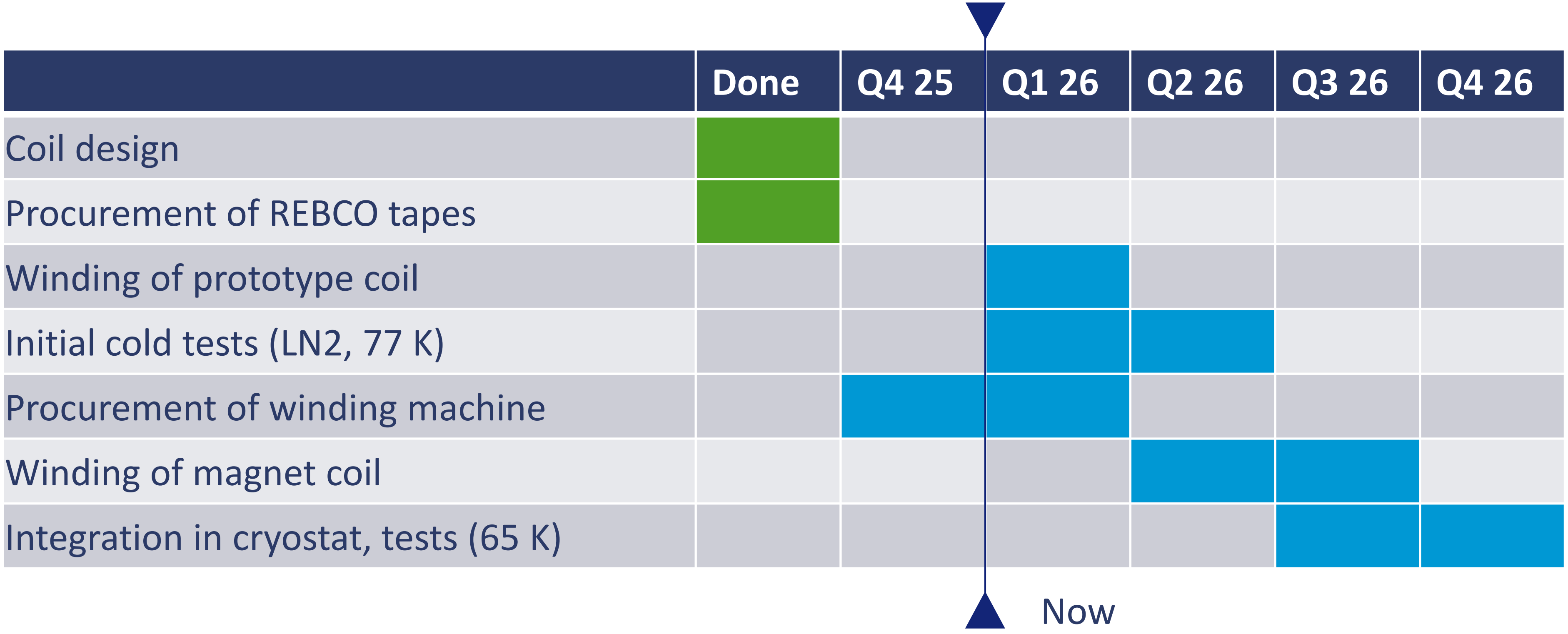
α, β coupling gains

Code under development:

- **verification** (FEA **H-**form with h homogenized anisotropic resistance)
- **validation** (measurements taken from literature)

TEST PLAN

Timeline



First prototype coil manufactured and tested by Q2 2026

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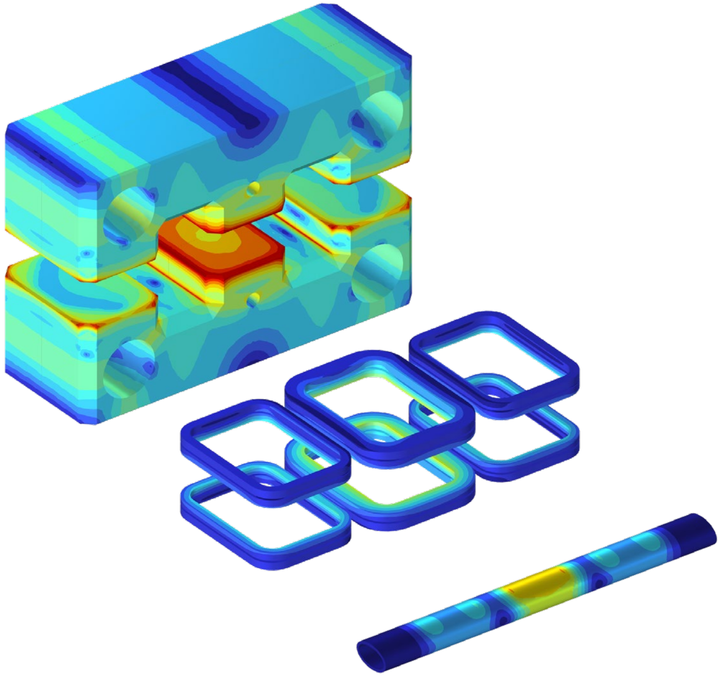
Summary

- REBCO tape for compact and tunable wiggler
- Design driven by simplicity, robustness, feasibility
- Iron optimized with RADIA on HPC cluster + COMSOL



Outlook

- Completion of cryostat design
- Quench analysis and testing on prototype coil
- Coil fabrication, assembly and test of the wiggler

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Many thanks to

IDM : C. Benabderrahmane, F. Bidault, J. Cavernot, B. Cottin, G. Giroud, M. Michel, F. Perratone, L. Samaille, R. Versteegen

ISDD: F. Cianciosi, F. Villard, L. Eybert, B. Pelissier

EXP-BM18: P. Tafforeau

ASD: Q. Qin

Thank you for your attention!

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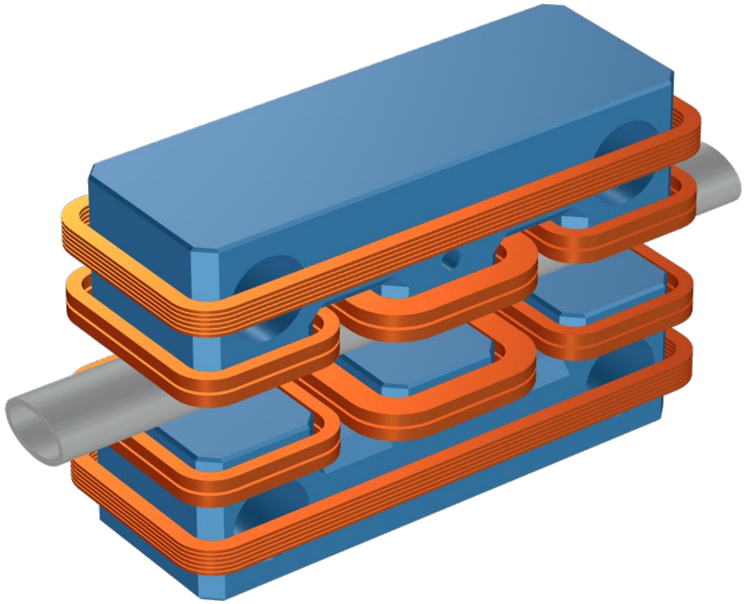
Backup

Magnet

Parameter	Unit	Value
Dimensions (L,W,H)	mm	200, 90, 120
Period	mm	70
Gap (physical)	mm	20
Peak magnetic field	T	1.58
Deflection	-	10.3

Coil

Nominal current	A	70
Self inductance	mH	55
Op. temperature	K	65
Load line	-	0.65

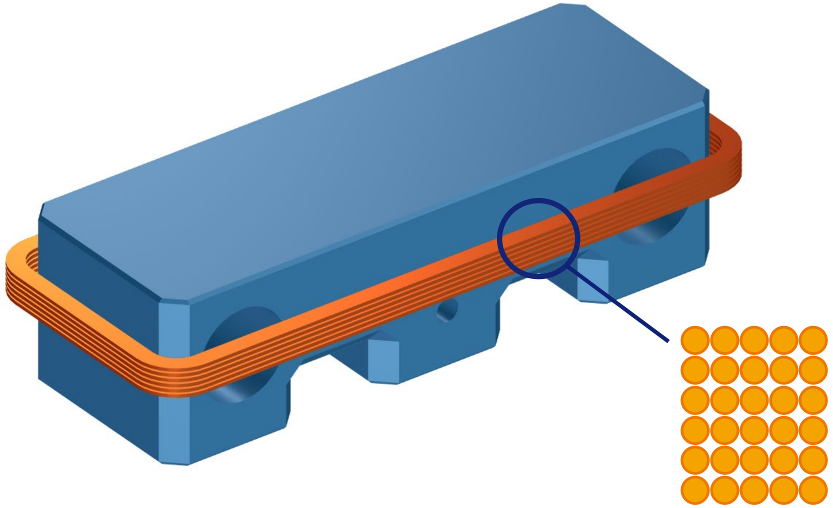


3D simplified rendering of the wiggler assembly

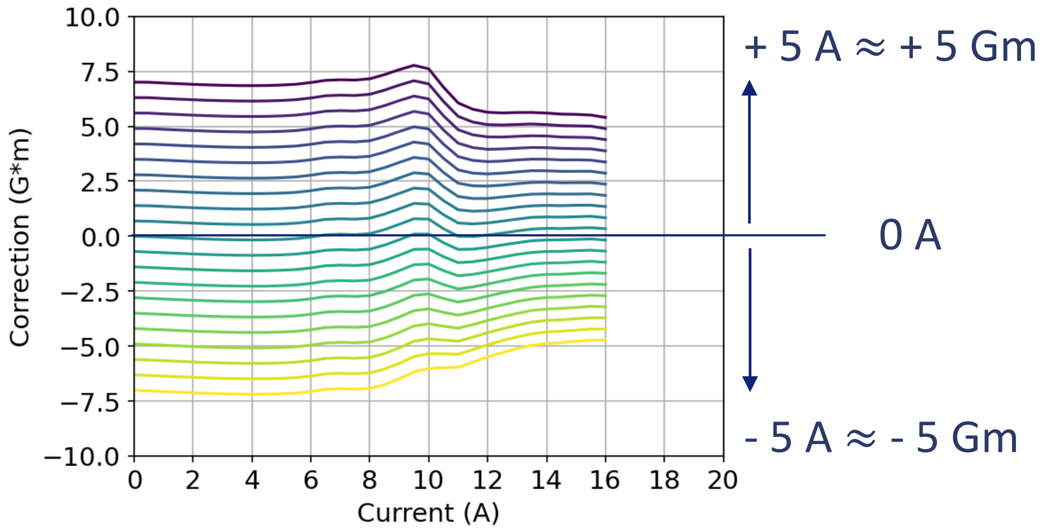
L. Bortot

Residual field errors:

- Uncertainty and inhomogeneity in material properties (iron yoke, REBCO tape)
- Mechanical and assembly tolerances
- Dynamic effects (Iron hysteresis, screening currents, tape defects)



Upper correction winding:
30 turns of 1mm2 copper wire



Contribution to 1^{st} field integral

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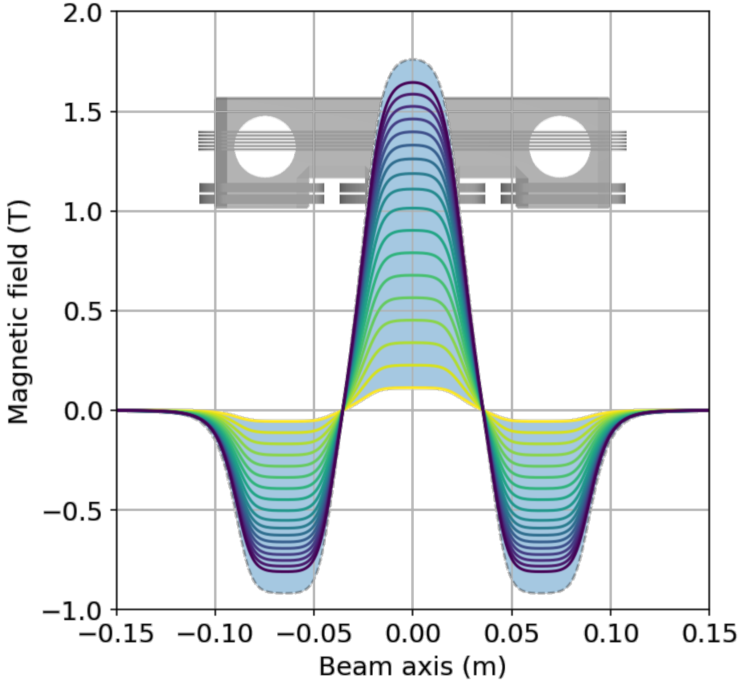
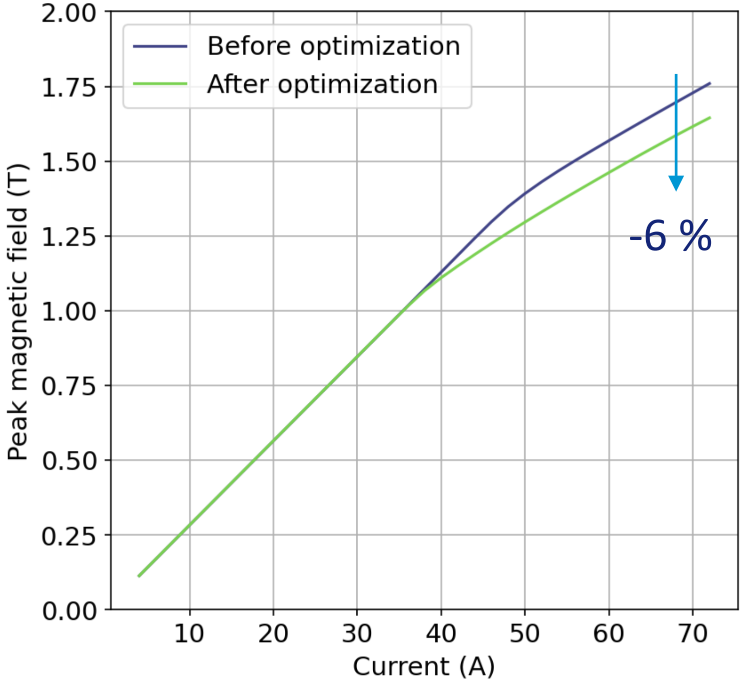
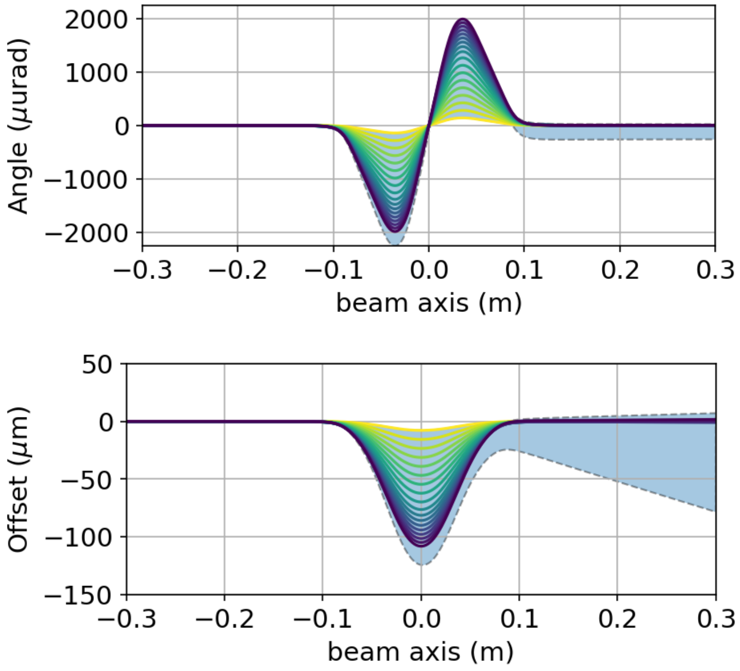
Magnetic field quality results



Magnetic field as function of current



Magnetic transfer function



Beam angle (top) and offset (bottom)

First and second field integrals corrected

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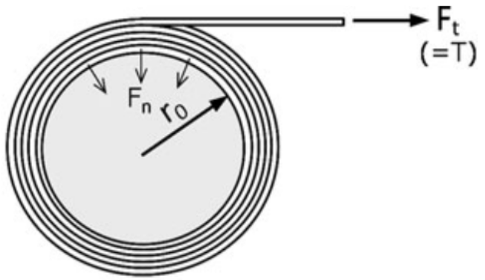
Hypothesis

Winding layers as series of cylinders

Thin-wall approximation (Hoop-to-radial stress relation)

$$\sigma_{\mathrm{n}} = \frac{1}{\eta}\,\frac{F_{\mathrm{t}}}{\mathrm{S}_{\mathrm{t}}}\sum_{n=1}^{N_{\mathrm{t}}}\frac{1}{\frac{r_0}{t_{\mathrm{t}}}+n}$$



F_{t} [N] applied tensile force

S_{t} [mm^2] tape surface

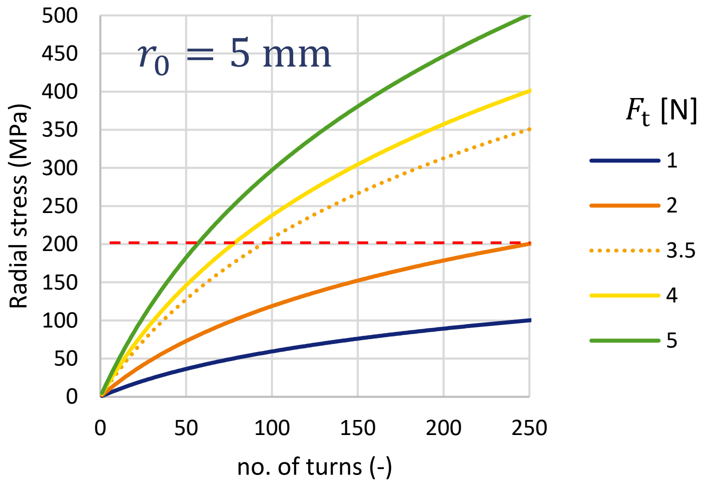
η [-] effective contact surface (5% from SEM)

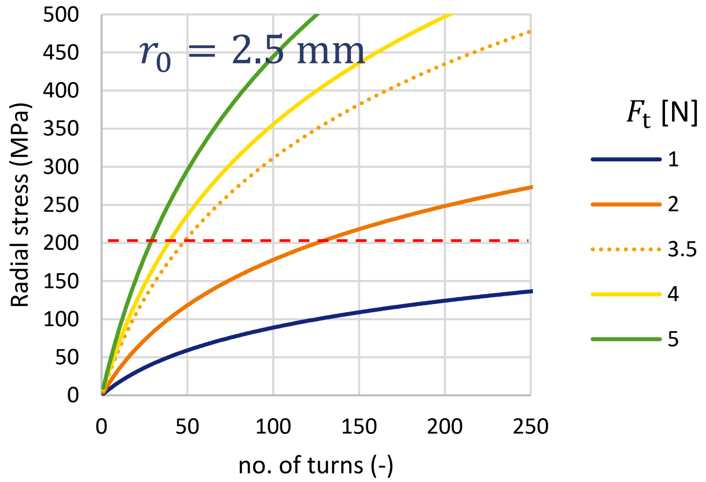
r_0 [mm] coil inner radius

t_{t} [mm] tape thickness

N_{t} [-] number of turns in the pancake

Challenge for small radius, narrow tape, many turns



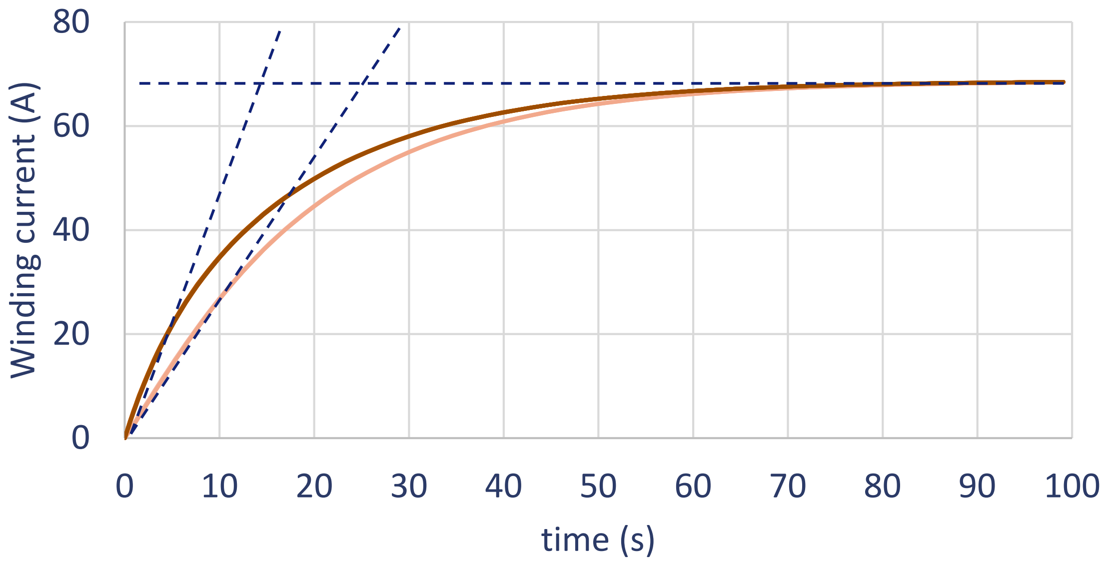


Radial stress as a function of number of turns

NO INSULATION COIL: ESTIMATION OF TIME CONSTANTS

	Unit	WI_C	WI_E	COIL
Self inductance (sim)	mH	5.1	1.7	34
Contact resistivity (meas*)	$m\Omega \cdot mm^2$	5.0	5.0	
Radial resistance	$m\Omega$	0.6	0.3	
Time constant	s	8.5	5.7	~25

(*) measured on a similar winding



SPICE model of 12 windings in series electrical connection

Inductance matrix calculated with FEM

Lorenzo Bortot

INDUCTANCE MATRIX

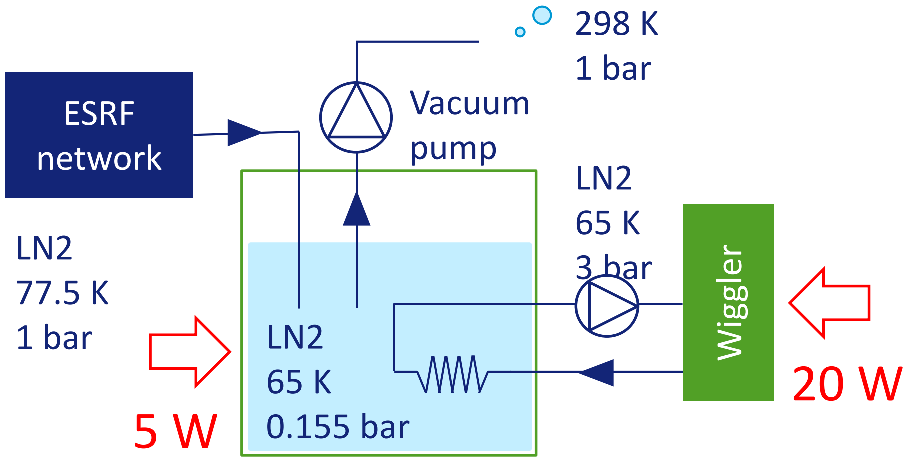
1.85E-03	1.52E-03	5.38E-04	4.61E-04	1.28E-04	1.35E-04	4.76E-05	4.35E-05	1.28E-04	1.35E-04	4.76E-05	4.35E-05
1.52E-03	2.01E-03	4.61E-04	3.99E-04	1.36E-04	1.54E-04	4.23E-05	3.84E-05	1.36E-04	1.54E-04	4.23E-05	3.84E-05
5.38E-04	4.61E-04	1.85E-03	1.52E-03	4.76E-05	4.35E-05	1.28E-04	1.35E-04	4.76E-05	4.35E-05	1.28E-04	1.35E-04
4.61E-04	3.99E-04	1.52E-03	2.01E-03	4.23E-05	3.84E-05	1.36E-04	1.54E-04	4.23E-05	3.84E-05	1.36E-04	1.54E-04
1.28E-04	1.36E-04	4.76E-05	4.23E-05	6.17E-04	5.07E-04	1.75E-04	1.56E-04	-3.88E-05	-3.98E-05	-3.60E-05	-3.62E-05
1.35E-04	1.54E-04	4.35E-05	3.84E-05	5.07E-04	6.69E-04	1.55E-04	1.40E-04	-3.97E-05	-4.08E-05	-3.61E-05	-3.63E-05
4.76E-05	4.23E-05	1.28E-04	1.36E-04	1.75E-04	1.55E-04	6.17E-04	5.07E-04	-3.60E-05	-3.62E-05	-3.88E-05	-3.98E-05
4.35E-05	3.84E-05	1.35E-04	1.54E-04	1.56E-04	1.40E-04	5.07E-04	6.69E-04	-3.61E-05	-3.63E-05	-3.97E-05	-4.08E-05
1.28E-04	1.36E-04	4.76E-05	4.23E-05	-3.88E-05	-3.97E-05	-3.60E-05	-3.61E-05	6.17E-04	5.07E-04	1.75E-04	1.56E-04
1.35E-04	1.54E-04	4.35E-05	3.84E-05	-3.98E-05	-4.08E-05	-3.62E-05	-3.63E-05	5.07E-04	6.69E-04	1.55E-04	1.40E-04
4.76E-05	4.23E-05	1.28E-04	1.36E-04	-3.60E-05	-3.61E-05	-3.88E-05	-3.97E-05	1.75E-04	1.55E-04	6.17E-04	5.07E-04
4.35E-05	3.84E-05	1.35E-04	1.54E-04	-3.62E-05	-3.63E-05	-3.98E-05	-4.08E-05	1.56E-04	1.40E-04	5.07E-04	6.69E-04

CRYOGENIC SYSTEM

Specs

Parameters	Unit	Value
Total heat load	W	25
Consumption LN2	l/day	12.5
Cryo-pump flow rate	l/h	20
ΔT secondary circuit	K	2.2
Pumped LN2 gas	m3/h	0.55

Vacuum Pumping on LN2 bath



Cryocooler (Gifford / Pulse-tube)