High Temperature Superconducting Tapes for Undulators

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Outline

- Motivation for short period high field undulators
- Technology comparison: superconducting versus permanent magnet undulators
- HTS tape SCUs
  - Advantages
  - Challenges
  - EuMAHTS
- Summary

Novel undulators: short period and high field

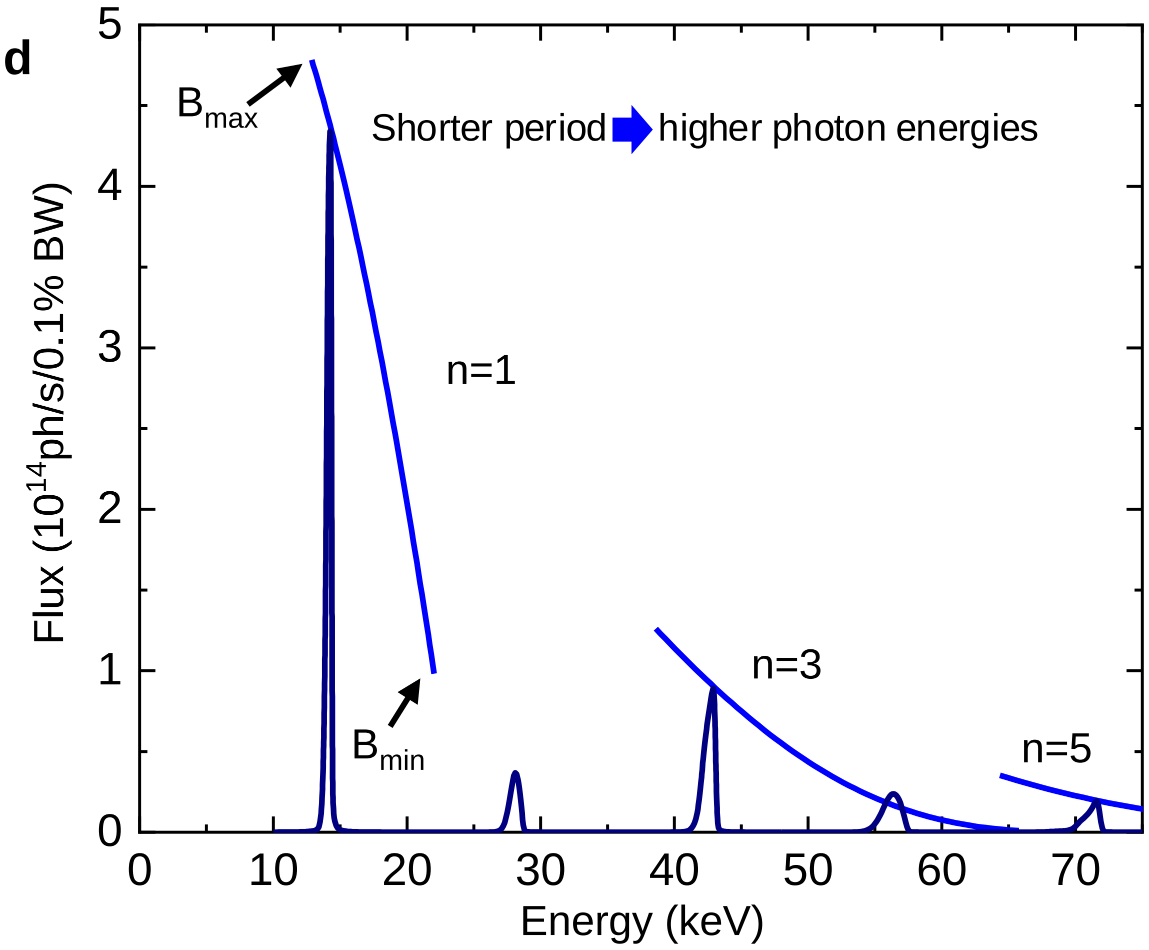
- **Novel technolgies** to reach **short period and high field undulators** leading to
  - **harder X-rays with larger tunability** in the present accelerators
  - more sustainable and compact accelerators with **lower electron beam energies** to achieve present photon energy range

$$\lambda = \frac{\lambda_U}{2\,n\,\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$K = \frac{e}{2\pi mc} B_0\ \lambda_U = 0.9336\ B_0[T]\ \lambda_U[cm]$$

- **Shorter period => higher photon energies**

- **Higher field => larger tunability of photon energies**



The position of the harmonics is shifted by changing the on axis peak magnetic field B_0

Short period high field undulators for FELs

$$P \propto e^{2z/L_G}$$

$$L_G \propto \lambda_U^{1/3} f(K)$$

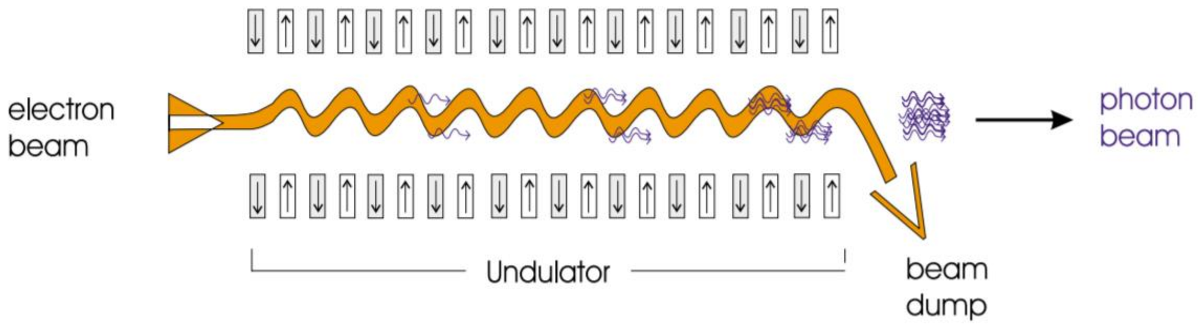
- For fixed electron beam energy and K,
a **shorter λ_U** implies a **shorter gain length L_G**

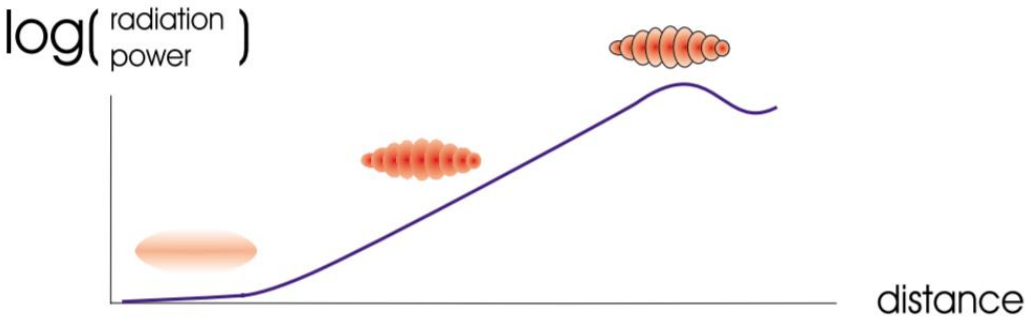
- Shorter saturation length ⇨ shorter undulator line

⇩

- Savings in civil construction cost

- By decreasing λ_U, the same or an increased photon energy tunability is obtained by increasing B_{max}

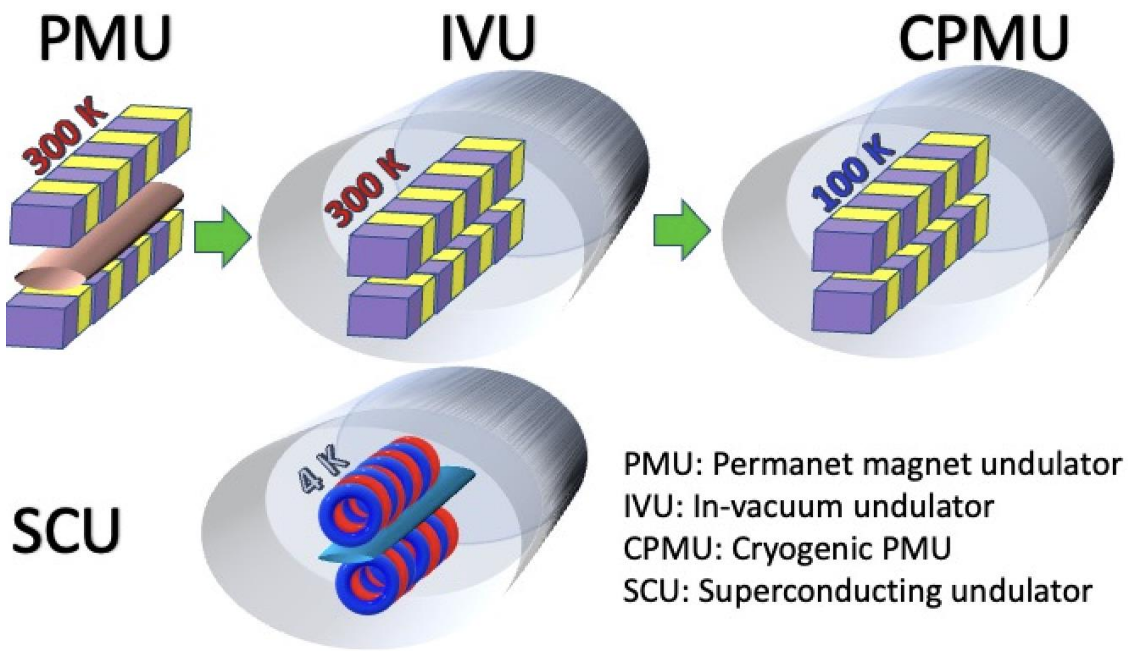




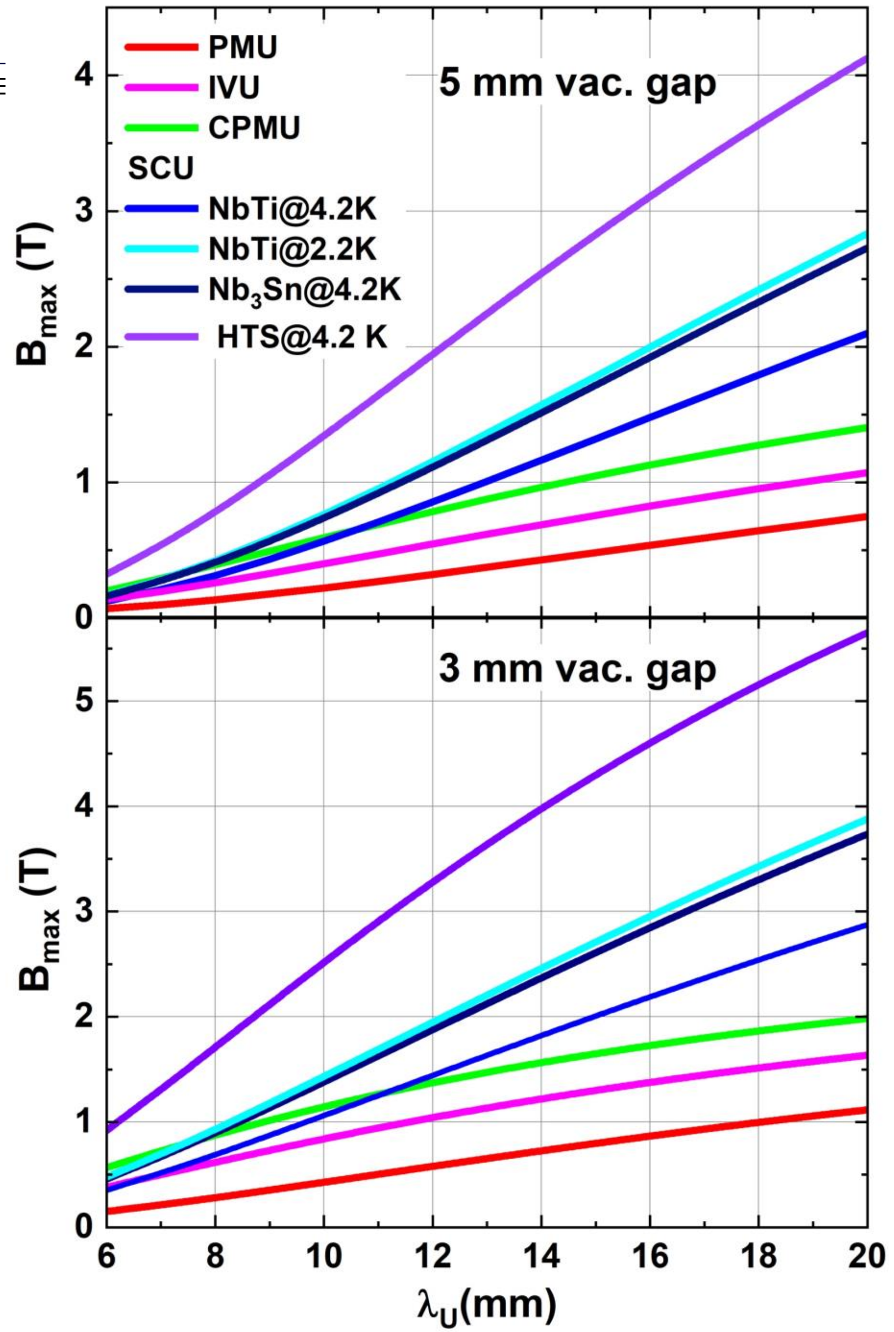
https://photonscience.desy.de/research/students__teaching/sr_and_fel_basics/fel_basics/tdr_from_synchrotron_radiation_to_a_sase_fel/index_eng.html

Technology comparison: SCUs vs. PMUs

- Technology development to increase B_{max}



- Further advantage is radiation hardness widely demonstrated for NbTi magnets (i.e. HERA, Tevatron, LHC)

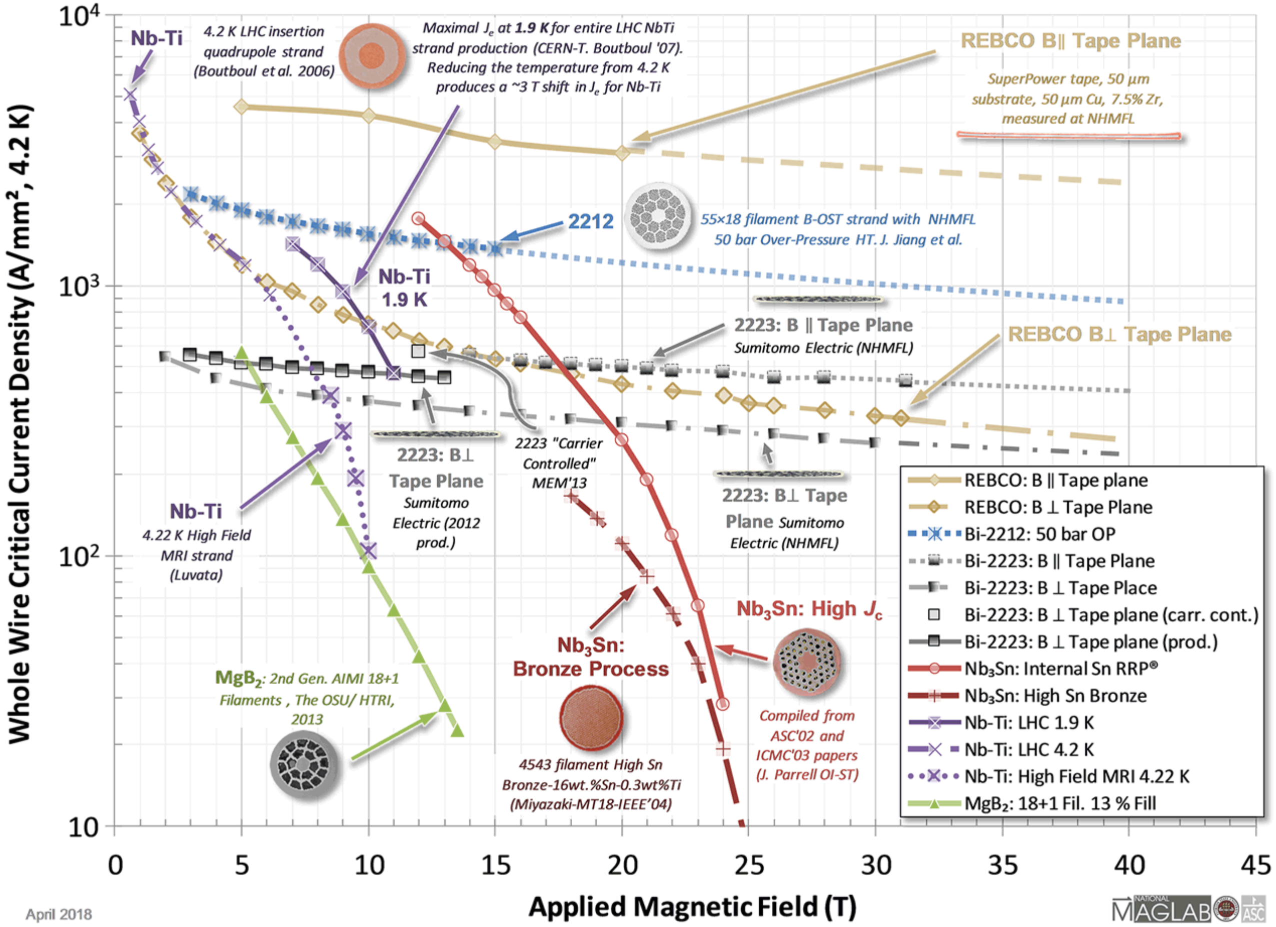


temperature margin SCU NbTi: 1 K and Nb_3Sn:~ 2.5 K
HTS (High Temperature Superconductors) ~ 11 K

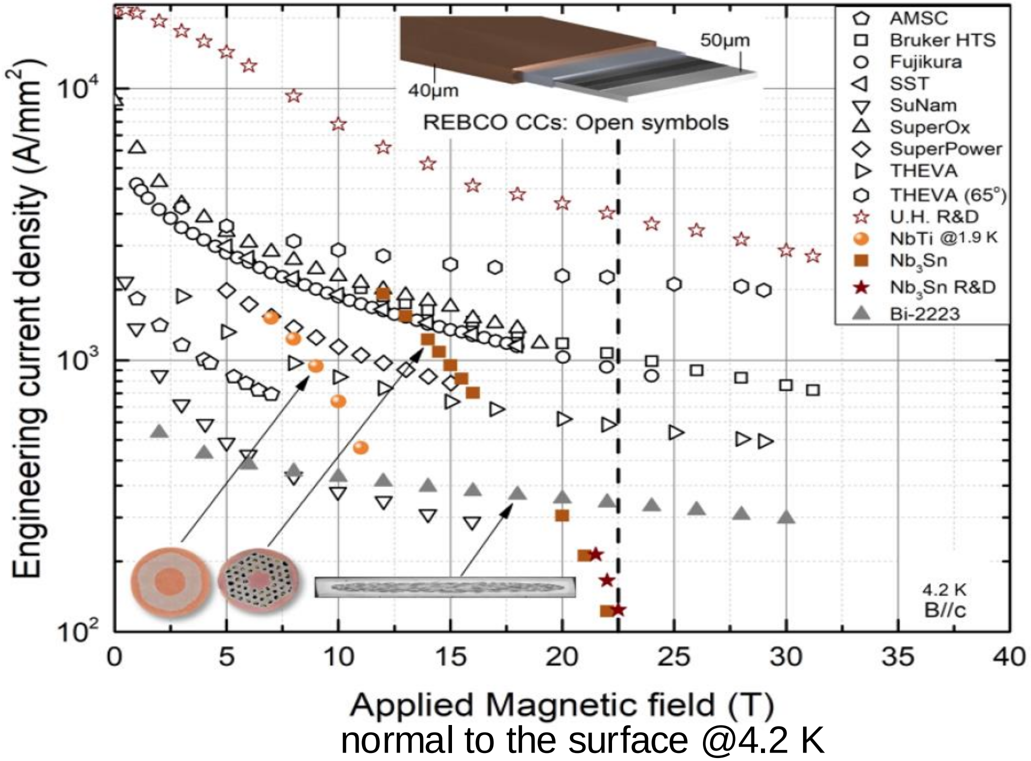
S. Casalbuoni et al., Front. Phys. Sec. Interdisciplinary Physics Volume 11 - 2023

HTS tape engineering critical current

https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots/



A .C. Wulff et al 2021 Supercond. Sci. Technol. 34 053003



Values scaled to 4 mm wide tape with 50 µm substrate with 40 µm Copper stabilizer, except AMSC

2018 => 2021

Development process of 2G-HTS tapes

B perpendiciular
to the HTS tape surface

Continent	R&D and production institution (country)	Buffer layer and rebco-layer epitaxial route	Single tape current-carrying Record (Year)	Current-carrying capacity of tapes under magnetic field (B//c)
Asia	SuNAM (South Korea)	IBAD + RCE	275 A / 470 m (2010) 355 A / 920 m (2011) 422 A / 1000 m (2012) 579 A / 978 m (2014) 625 A / 1000 m (2015)	I_c(4.2 K, 18 T) > 115 A (2017)
	Fujikura (Japan)	IBAD + PLD	306 A / 368 m (2007) 350 A / 504 m (2008) 572 A / 816 m (2011) 580 A / 1040 m (2012)	I_c(4.2 K, 18 T) ≈ 750 A (2020)
	SWCC (Japan)	IBAD + MOD	310 A / 500 m (2008)	I_c(4.2 K, 18 T) > 125 A (2018)
	Samri (China)	IBAD + MOCVD	150 A / 1000 m (2014) 570 A / 1130 m (2016)	I_c (4.2 K, 10 T) = 710 A (2022)
	SCSC (China)	IBAD + MOD	350 A / 500 m (2018)	I_c(4.2 K, 12 T) = 300 A (2022)
	SST (China)	IBAD + PLD	550 A / 1000 m (2018)	I_c(4.2 K, 18 T) = 450 A (2019)
North America	SuperPower (America)	IBAD + MOCVD	173 A / 595 m (2007) 153 A / 1311 m (2008) 282 A / 1065 m (2009)	I_c(4.2 K, 18 T) > 125 A (2020)
	AMSC (America)	RABiTS + MOD	466 A / 540 m (2010)	I_c(4.2 K, 18 T) > 110 A (2018)
Europe	Bruker (Germany)	ABAD + PLD	260 A / 100 m (2009) 350 A / 270 m (2014) 330 A / 600 m (2016)	I_c (4.2 K, 18 T) = 454 A (2019)

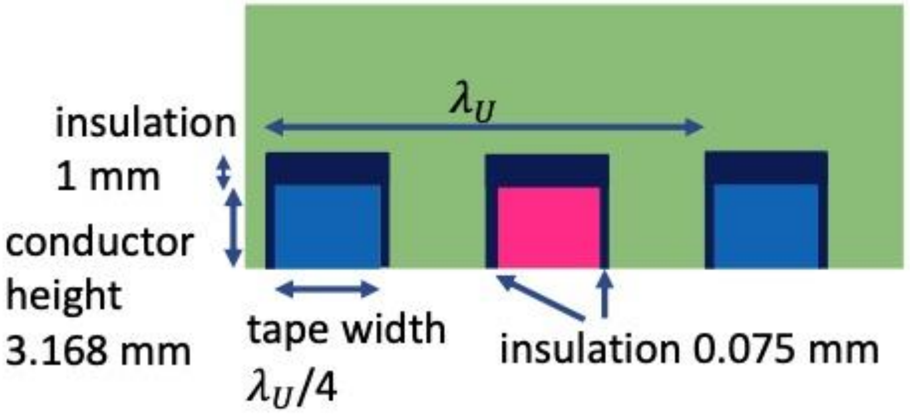
K. Wang et al., *Soft. Sci.* 2022, *2*, 12
http://dx.doi.org/10.20517/ss.2022.10

Development process of 2G-HTS tapes

- In the past 5 to 10 years:
  - increased engineering current density by a factor of 2-3 with potential to infcrease further
  - HTS tapes available from several companies in lengths ~ km
- Driving market FUSION: drive the cost from $10 kA/m to $kA/m

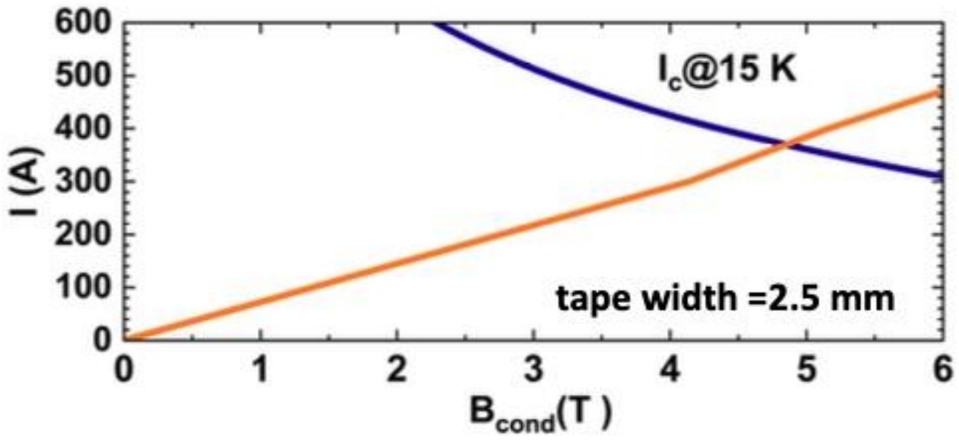
A .C. Wulff et al 2021 Supercond. Sci. Technol. 34 053003

HTS tape SCU



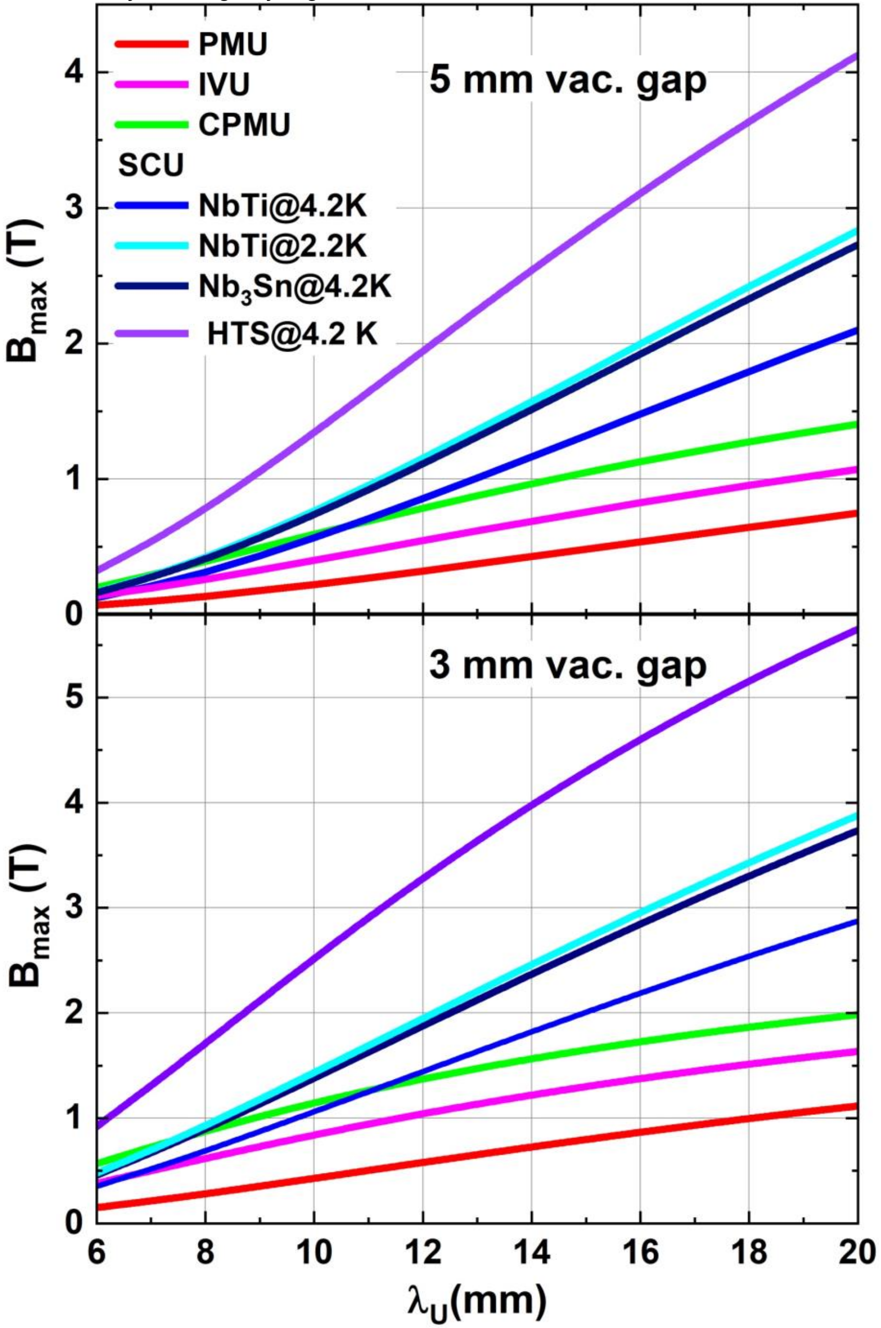
HTS tape
33 µm
no stabilizer
96 layers

Loadline for an HTS SCU with a period of 10 mm



Ic for field perpendicular to the HTS tape surface

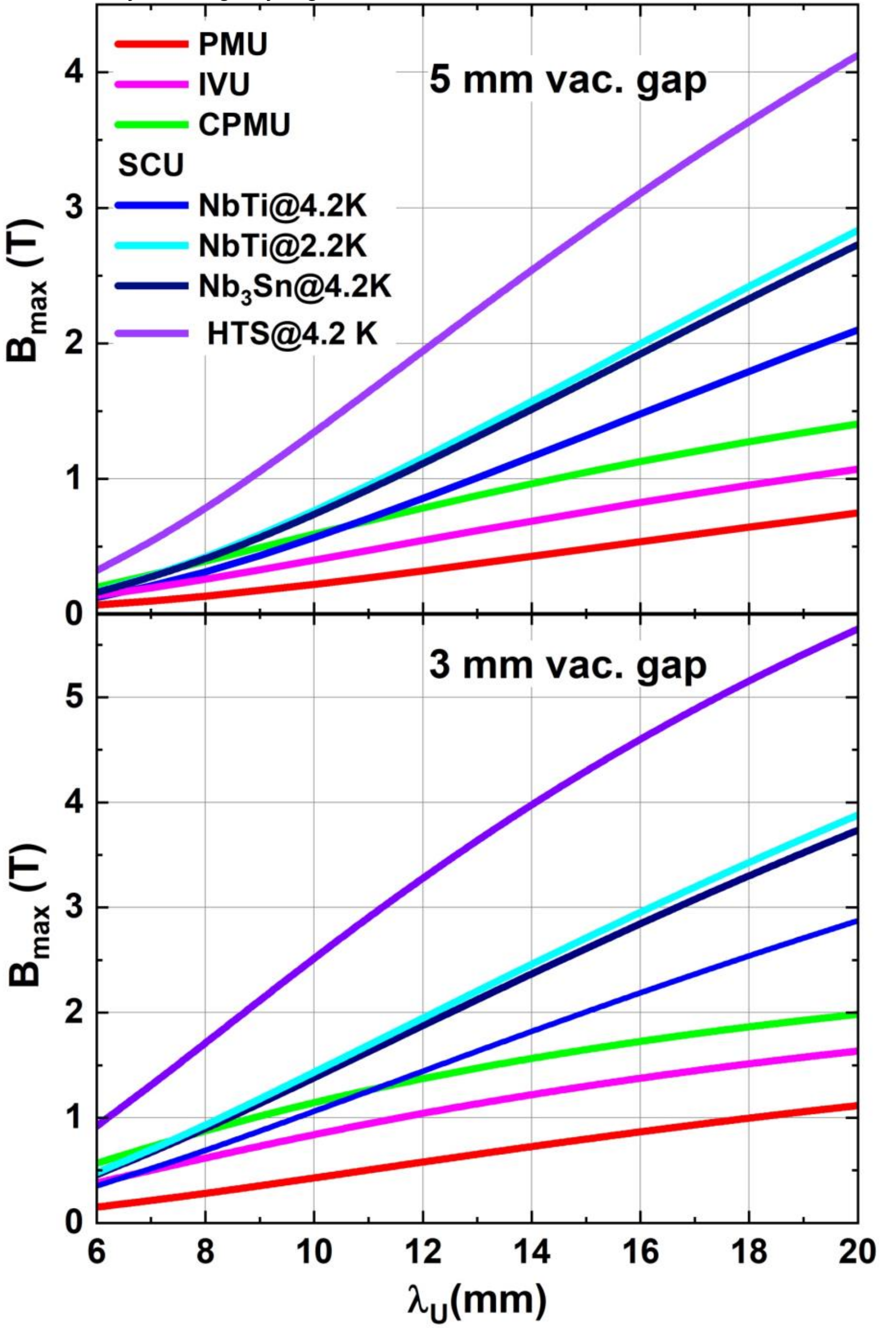
Temperature margin HTS ~ 11 K



HTS tape SCU

$\lambda_U > 12$ mm
beam stay clear = 5 mm
$B_{max} > 2$ T
T ≈ 4 K
Temperature margin ≈ 11 K

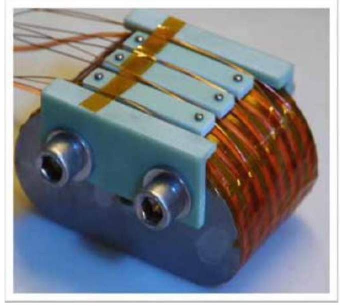
doubles B_{max} with respect to NbTi-SCUs @4.2 K

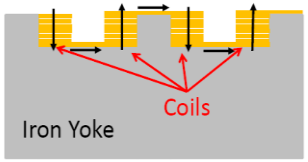


HTS undulators: possible geometries

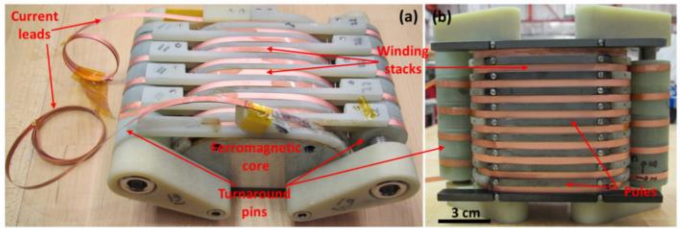
- HTS (High Temperature Superconducting) tapes and bulks
  - Not yet demonstrated in accelerator environment
  - HTS tape: Noell, KIT, ANL, FNAL and EuXFEL started

Planar HTS SCUs





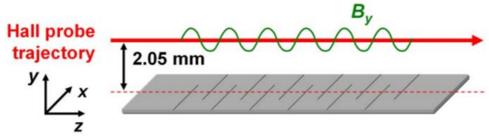
C. Boffo IDMAX10 Workshop, Lund 2010
C. Boffo, Th. Gerhard, PCT/EP2010/004656

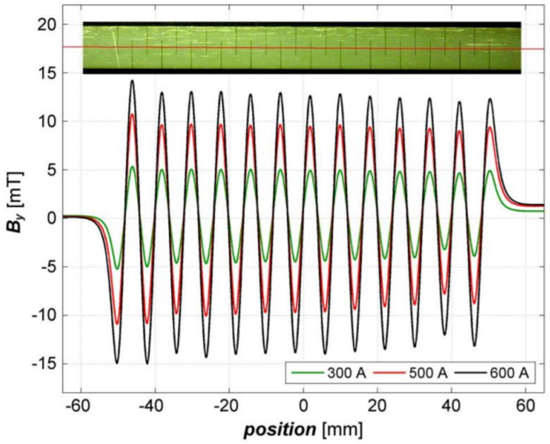


I. Kesgin et al., SUST 30 04LT01 2017

Period length = 16 mm
m. gap = 9.5 mm
Estimated
B = 1.0 T more than 30% NbTi@4K

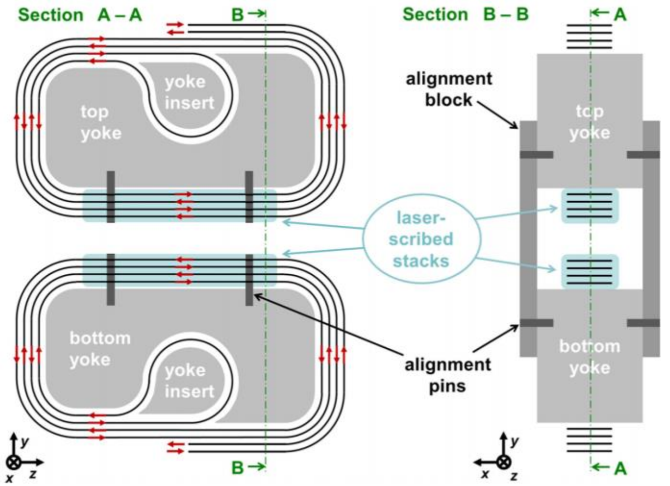
HTS structured SCU





Period length = 8 mm
m. gap = 2.5 mm
Estimated
w =12 mm B = 1.0 T
w > 20 mm B = 1.4 T

T. Holubek et al., IEEE Trans. on Appl. Supercond. 4602204 Vol. 23-3 (2013)



T. Holubek et al., SUST 30 115002 2017

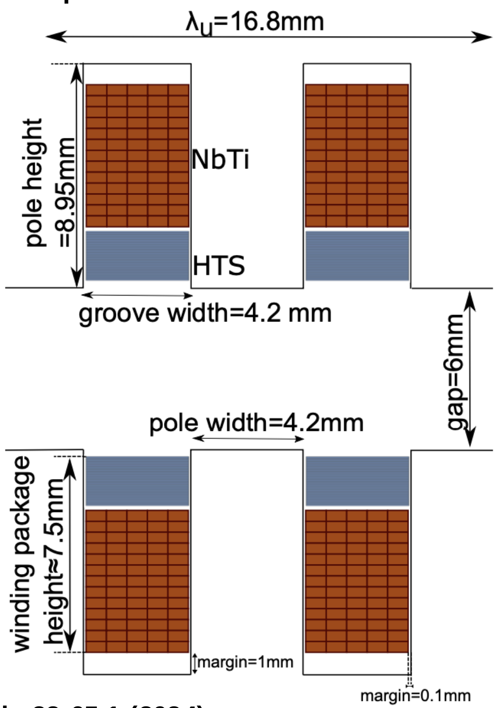
HTS tape SCUs

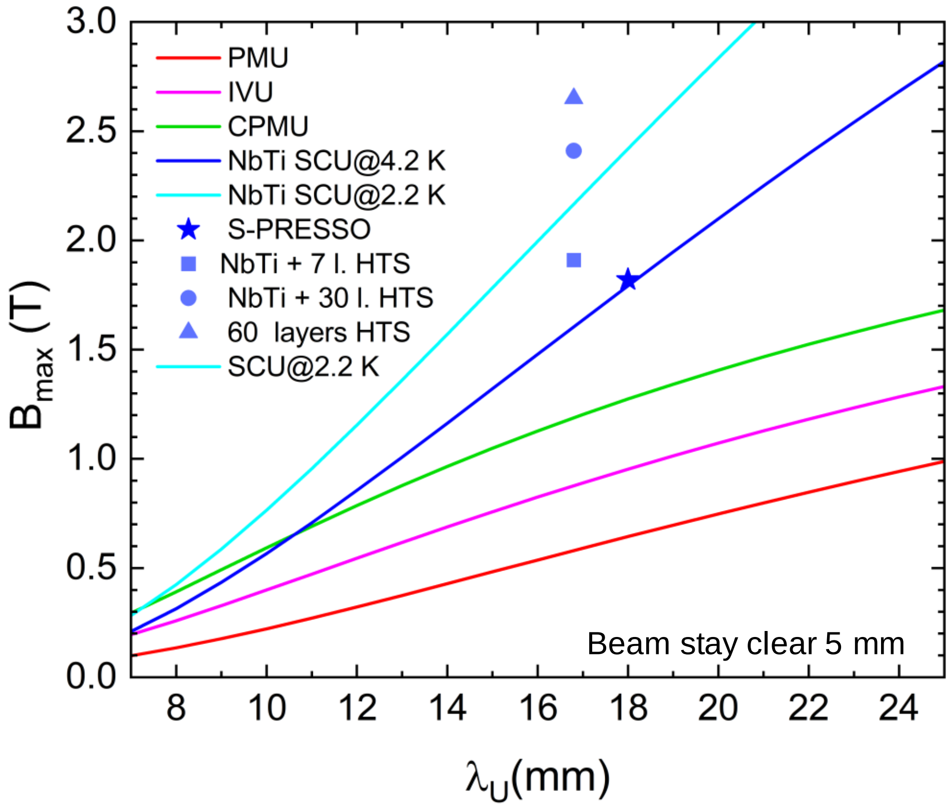
- Advantages:
  - Higher peak field on axis with respect to PMUs and other SCUs
  - The large temperature margin of the HTS allows to operate these coils at higher temperatures without losing in magnetic field performance, leading to more robust and/or sustainable operation with reduced cooling power
  - Compared to presently under development bulk HTS SCUs concepts, HTS tape SCUs allow practical tunability of the magnetic field and therefore photon energy
- Open issues:
  - Uniformity, repeatability, mechanical properties, quench protection, available length for the tape, and production rate of high quality HTS tape and bulk
- **HTS undulator technology is yet to be tested in a light source**

HybriSCU

- HybriSCU, a graded SCU combining NbTi and HTS tape has been proposed and studied
  - To use the high engineering current density of the HTS tape in the most effective location
  - To increase B_{max} and take advantage of the larger temperature margin of HTS tapes

Hybrid NbTi/HTS tape





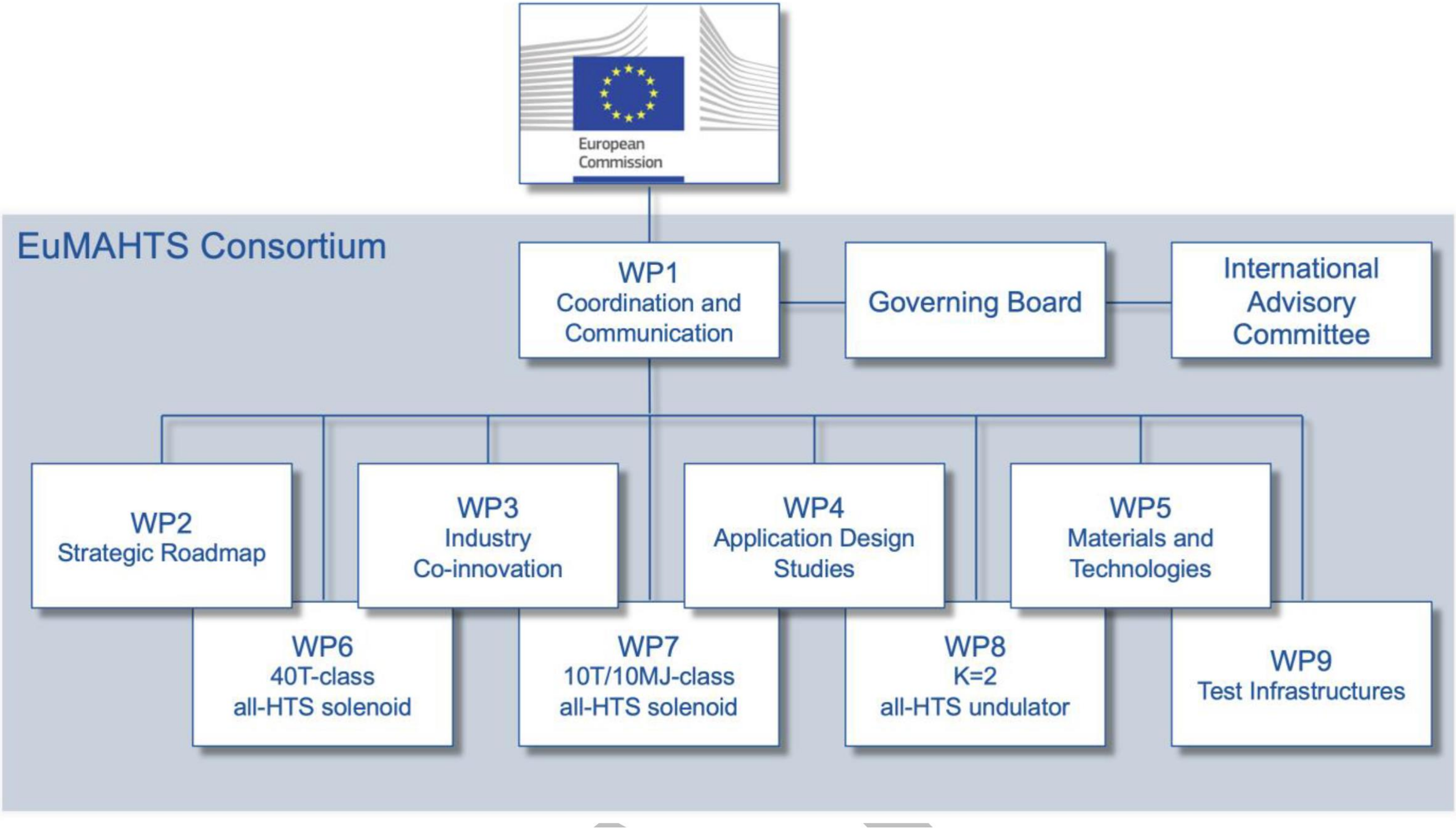
V. Grattoni and S. Casalbuoni, IEEE Trans. Appl. Supercond., 33-65 1 (2024)

EuMAHTS

- The prime objective of EuMAHTS (Magnet technology Advances for European research infrastructures through HTS) is to advance High Temperature Superconductor (HTS) magnet technology and demonstrate the perceived disruptive potential of this class of superconductors for multiple fields of scientific and societal application.
- Demonstrate higher magnetic field reach, but also to develop technology for energy efficient, compact, cost effective, and sustainable device
- Designing, building and testing three prototype magnets that implement a high degree of technology innovation
- Prepare European industry response to upcoming requests for such magnets, as well as facilitate market penetration of HTS magnet technology in a near future

Participant No. *	Participant organisation name
1 (Coordinator)	CERN
	CEA
	CIEMAT
	CUT
	EMFL
	ESRF
	EUXFEL
	GSI
	IFJPAN
	INFN
	KIT
	PSI
	TERA-CARE
	TAU
	UMIL
	UTWENTE
	UNIGE

EuMAHTS



WP8 – K=2 All-HTS Undulator, will design, produce and test a high field, short period undulator with technology relevant to achieve a 2 T field target, <15 mm period and 5 mm gap

EuMAHTS

- WP8 Objectives: Design, fabrication, and test an all-high-temperature superconductor (HTS) short period undulator (K=2, B=2T, p<15mm, g=5mm) to demonstrate the superior magnetic field performance of HTS compared to NbTi.
  - T8.1 – Coordination
  - T8.2 - Engineering design
  - T8.3 – Samples and models
  - T8.4 – Prototype fabrication
  - T8.5 – Prototype test and analysis

Summary

- HTS tape SCUs have the potential to sustantially outperform NbTi SCUs
- Presented advantages and open issues with respect to other technologies including HTS bulk SCUs
- HTS undulator technology is yet to be tested in a light source
- EuMAHTS proposal
- **It’s time to invest more resources in applying HTS tape for SCUs!**

Thank you for your attention !