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Quantitative Analysis of Undulator Technologies for CompactLight FEL

Recap of earlier comparative study for a set of 4 undulator technologies

New comparative study using revised data for all undulator technologies

Conclusions

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XLS Midterm Meeting, Helsinki, 1-4 July 2019

Initial Study

Relative Performance for Four Undulator Technologies

Undulator Comparison

- Quick comparison of different undulator technologies to motivate discussions
- Determined, for beam energies from 4 – 9 GeV, for different undulators:
  - the period for the FEL to tune from 8keV at minimum gap (or max field) to 16keV
  - the a_w parameter at 16keV
- Have calculated, using simple 1D model (no corrections for emittance, energy spread, diffraction)
  - The 1D saturation length and saturation power at 16keV for peak current 4kA
- Not intended to provide absolute answers to the performance but to illustrate the relative differences we could expect between the different undulator types and how the technology would affect our choice of beam energy, for example
- Achievable field: $$B = c_1 \exp\left(c_2 \left[\frac{g}{\lambda_w}\right] + c_3 \left[\frac{g}{\lambda_w}\right]^2\right)$$

	c_1	c_2	c_3	Comment
Cryogenic PMU	3.896	-4.022	0.529	ref: EuPraxia Report D6.1, 2016
DELTA helical	1.45	-1.28	-2.24	ref: A. B. Temnykh, PR-STAB 11, 120702, 2008
Hybrid Planar	3.67	-5.08	1.54	ref: P. Ellaume et al, NIM A455, 2000, 503-523
SCU Helical	N/A	N/A	N/A	Polynomial fit to 3D model data from Vicky Bayliss, STFC

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Undulator Comparison – 1D Calcs

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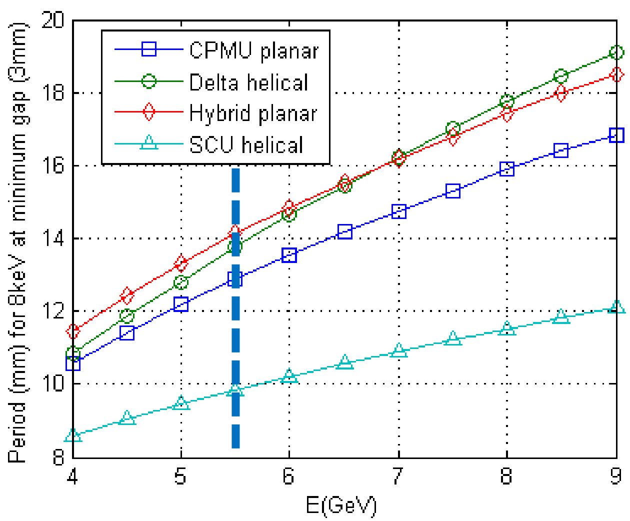
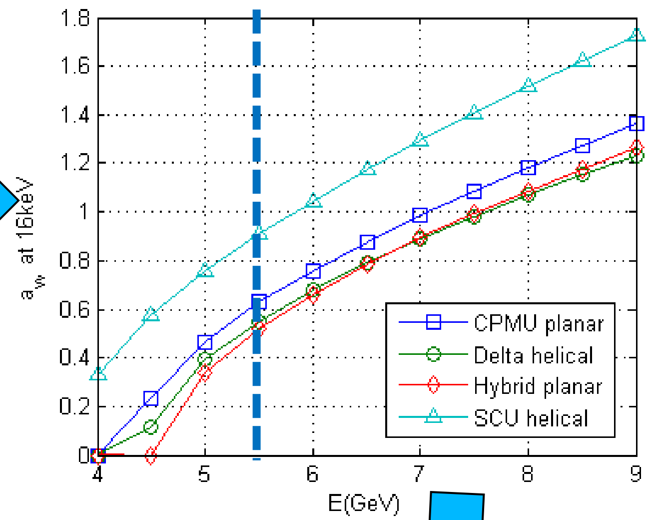
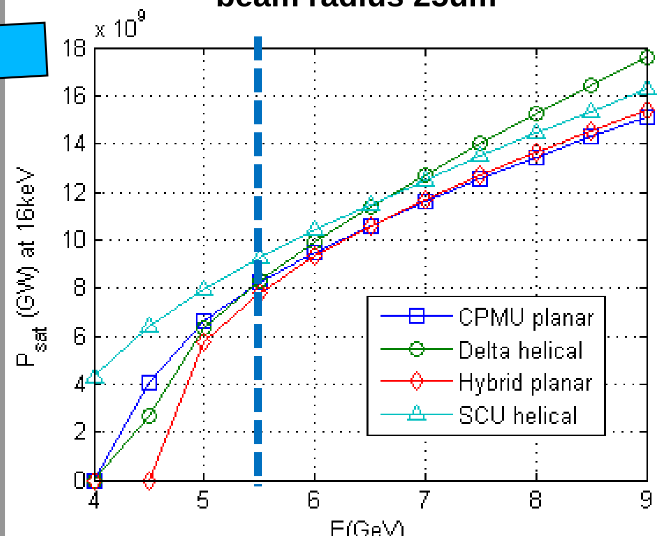
Period required for 8keV at minimum gap of 3mm



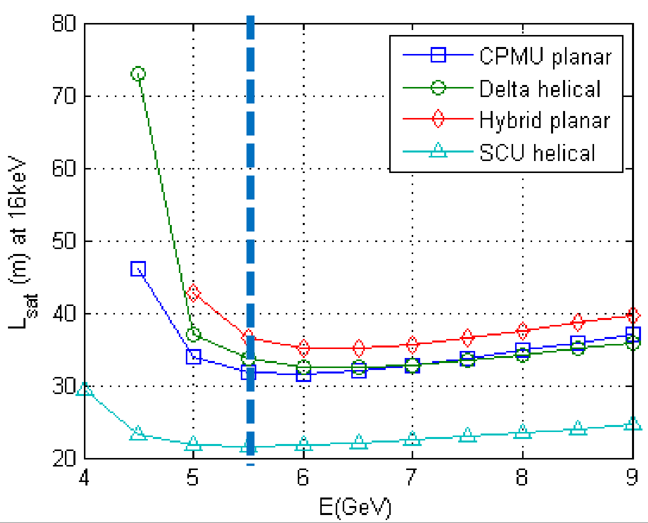
Corresponding a_w at 16keV



1D saturation power for peak current 4kA, beam radius 25um



1D saturation length for peak current 4kA, beam radius 25um



CONCLUSION

Choose nominal beam energy of ***5.5 GeV***

This is ***lower than SwissFEL*** (even though photon reach is higher)

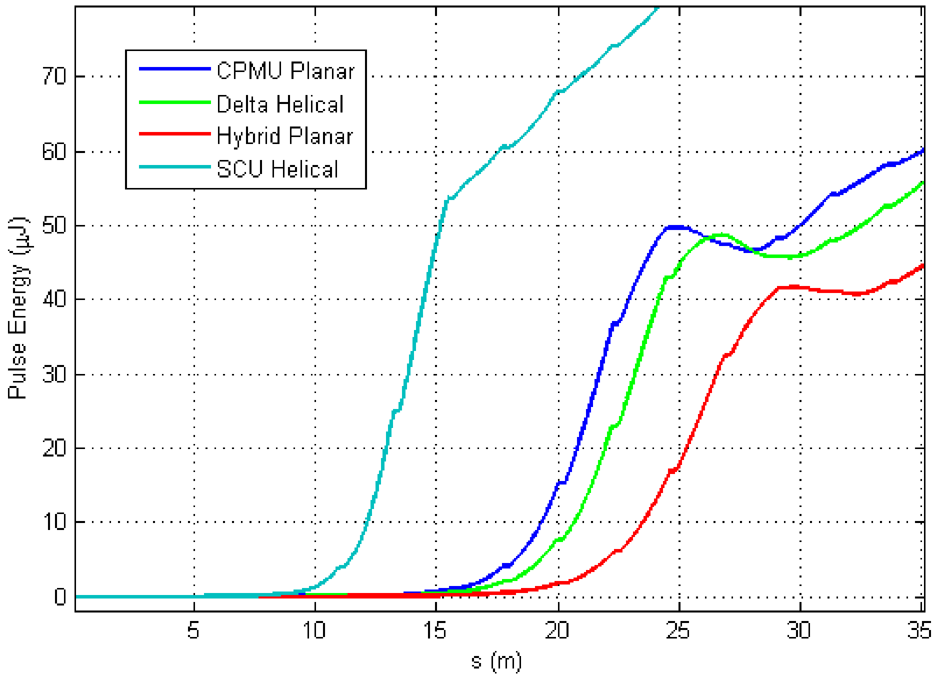
Still allows choice of undulators

Also note that undulator technologies with strongest fields:

Allow E < 5.5GeV,
or
Give better performance at 5GeV
or
some combination of both

Genesis Time Dependent Simulations

Parameter	Value
Photon Energy	16 keV`
Beam Energy	5.5 GeV
Normalised emittance	0.2 mm-mrad
RMS Energy Spread	1e-4
Bunch duration	5.45 fs
Bunch shape	Flat top
Charge	27pC



	CPMU	Delta	Hybrid	SCU
Psat (GW)	9.1	8.9	7.6	9.8
Lsat (m)	24.5	26.5	29.1	15.6
Pulse Energy (μJ)	49	48	29	54
FWHM Bandwidth	9.9e-4	9.7e-4	9.9e-4	1.1e-3
Peak Brightness #ph/s/mm^2/mrad^2/0.1%bw	2.4e33	2.4e33	2.0e33	2.2e33

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New Study (in D5.1 Report)

Relative Performance for All Undulator Technologies

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- The approach + code used by Vitaliy Goryashko and Alan Mak was adopted
- Data was collated from all partners to parameterise the performance of the different undulator technologies in terms of maximum *K* vs period.
- The semi-analytical model of Ming Xie, which predicts the basic FEL output parameters (peak power P_{sat}, saturation length L_{sat}) was then combined with the analysis of Saldin which predicts longitudinal and transverse coherence.
- This allowed a realistic estimate of the FEL Peak Brilliance, *B*, which is a key parameter of interest to users because it tells them how many photons per second within a given bandwidth can be focussed onto a sample.
- Two 'Figures of Merit' were assessed, one relative, one absolute:
  - **The ratio between the peak brilliance and the saturation length B/L_{sat}.**
    This is useful because it combines performance with compactness and allows us to clearly see the ***relative merits*** of the different technologies
  - **The peak brilliance *B*.**
    This is useful because we have a defined user specification of $B > 10^{33}$ ph/s/mm^2/mrad^2/0.1%BW. We assume that in the interpratation of the results that we need a factor of two contingency to account for reductions in peak power and/or increases in BW due to wakefields, energy chirp, 'errors'.... i.e. our 'threshhold brightness is **$B > 2 \times 10^{33}$ ph/s/mm^2/mrad^2/0.1%BW**
- Assumed beam properties: Norm. emittance = 0.2 mm-mrad, RMS energy spread = 1e-4, peak current = 5kA, average β-function = 9m

Merit Function B/L_{sat} @ 4.5 GeV

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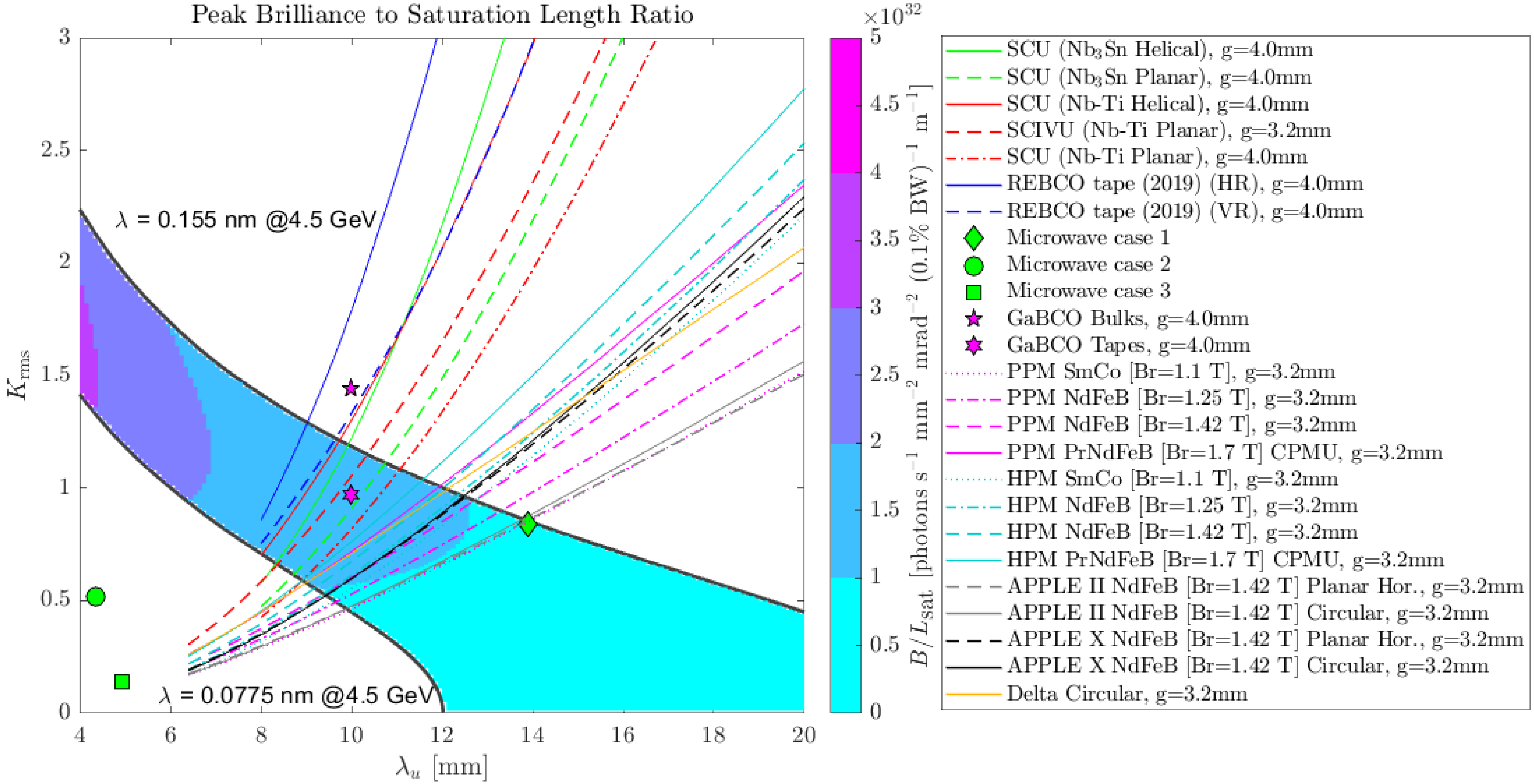
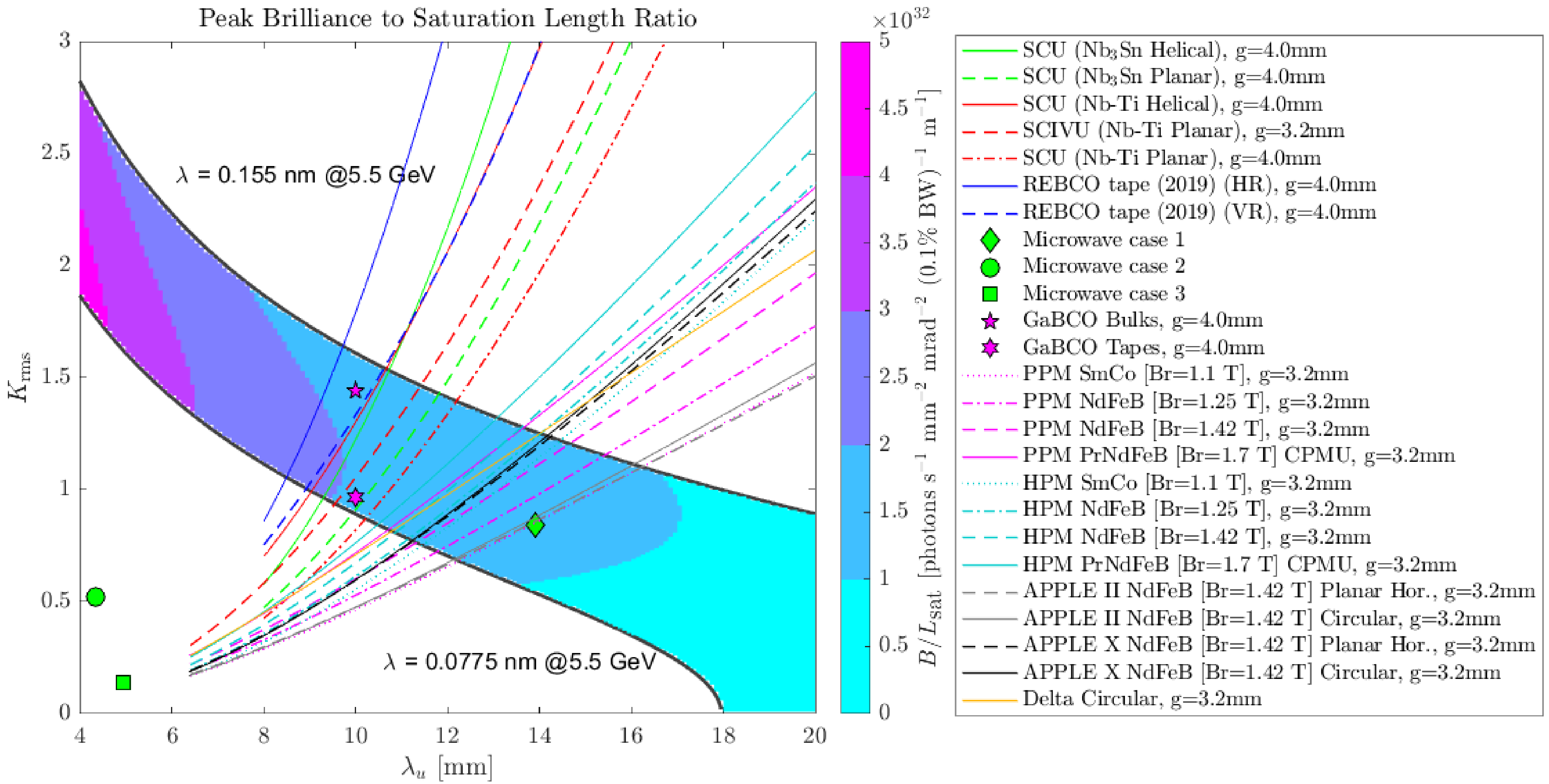


- ‘Weakest’ undulators can’t reach 0.0775nm wavelength
- ‘Strongest’ undulators have highest merit function

Merit Function B/L_{sat} @ 5.5 GeV



- All undulators can reach 0.0775nm
- ‘Weakest’ undulators have low merit function
- ‘Strongest’ undulators have highest merit function
- All merit functions have increased at higher beam energy

Merit Function B/L_{sat} @ 6.5 GeV

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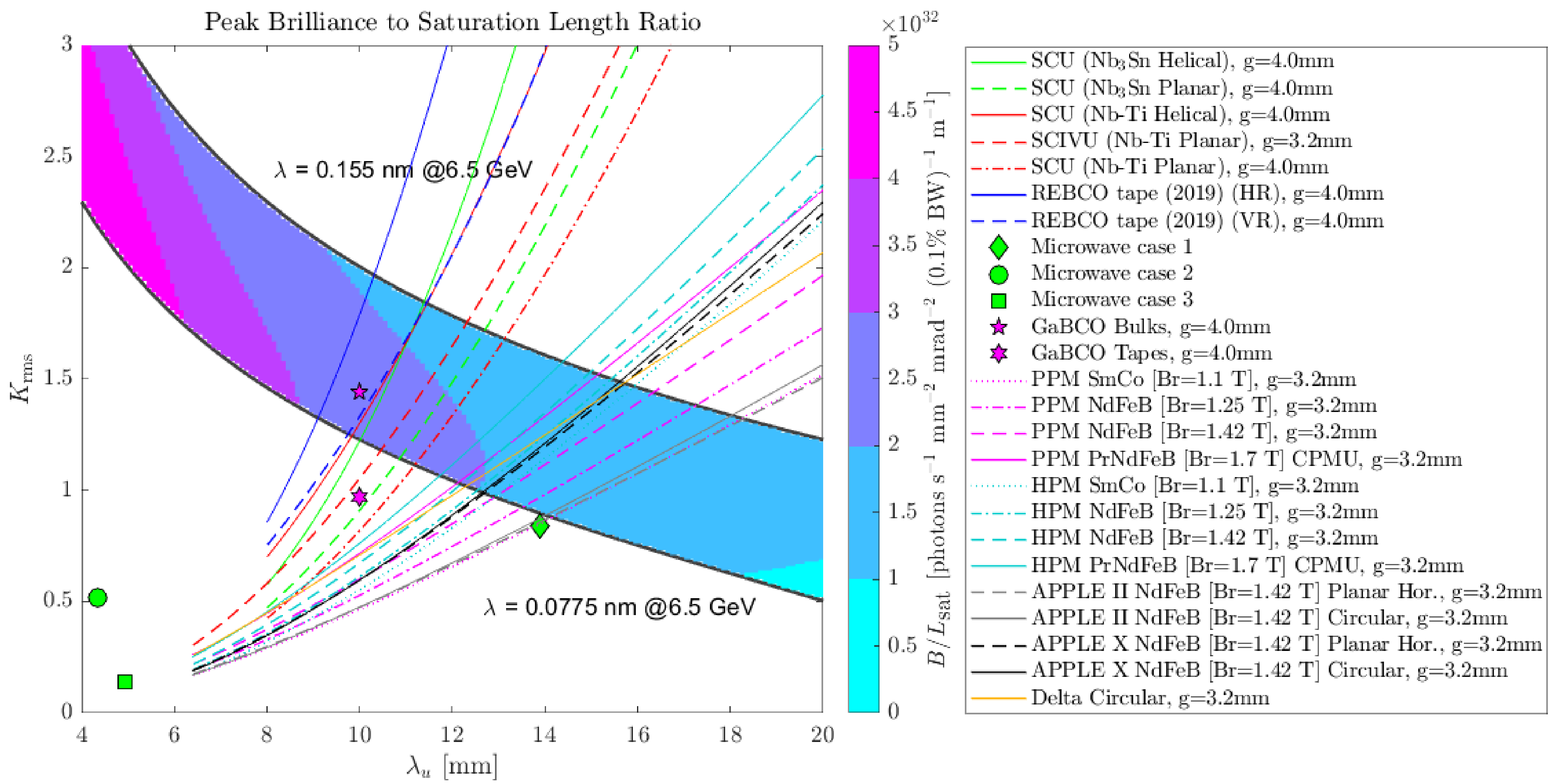
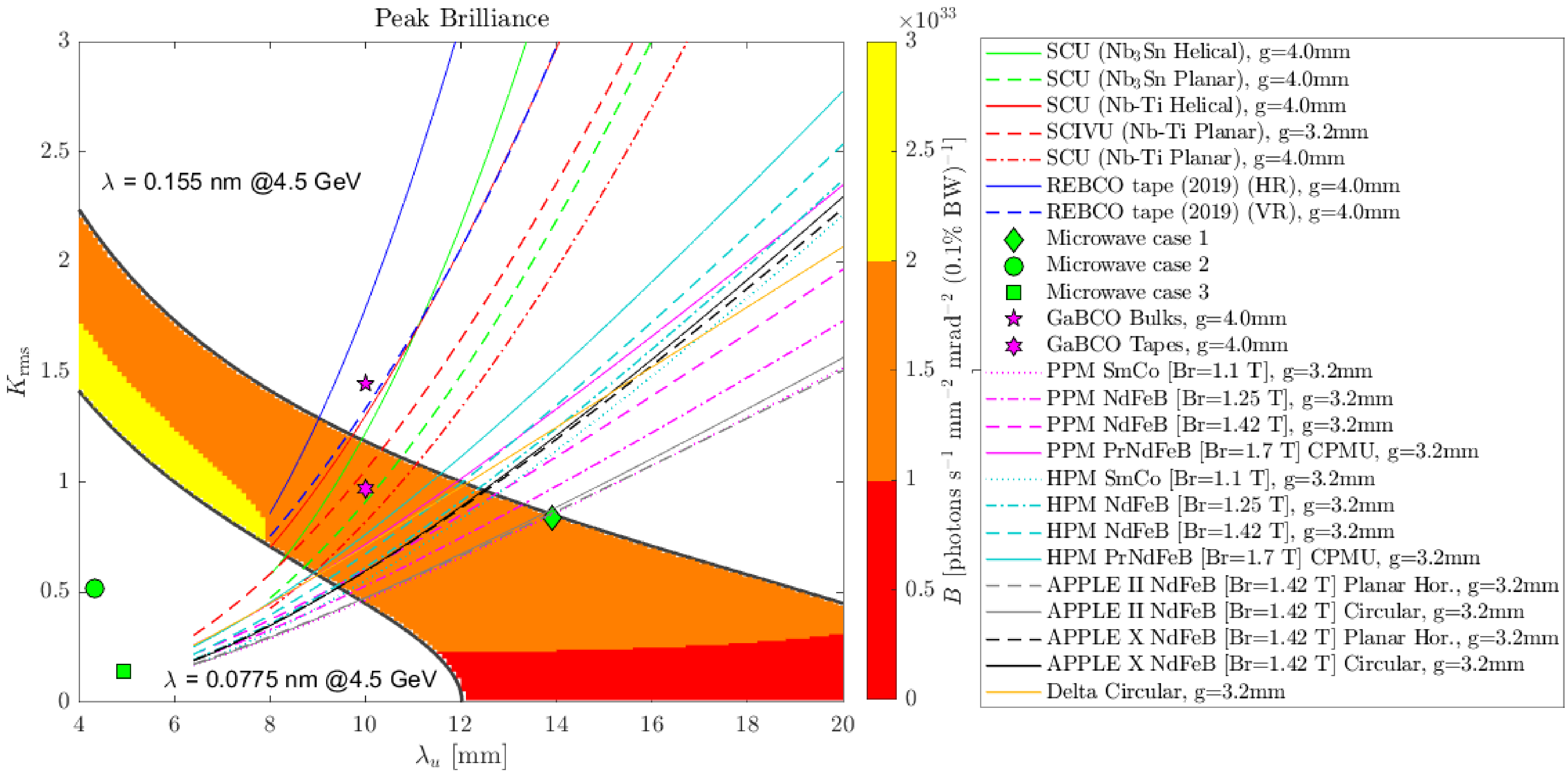


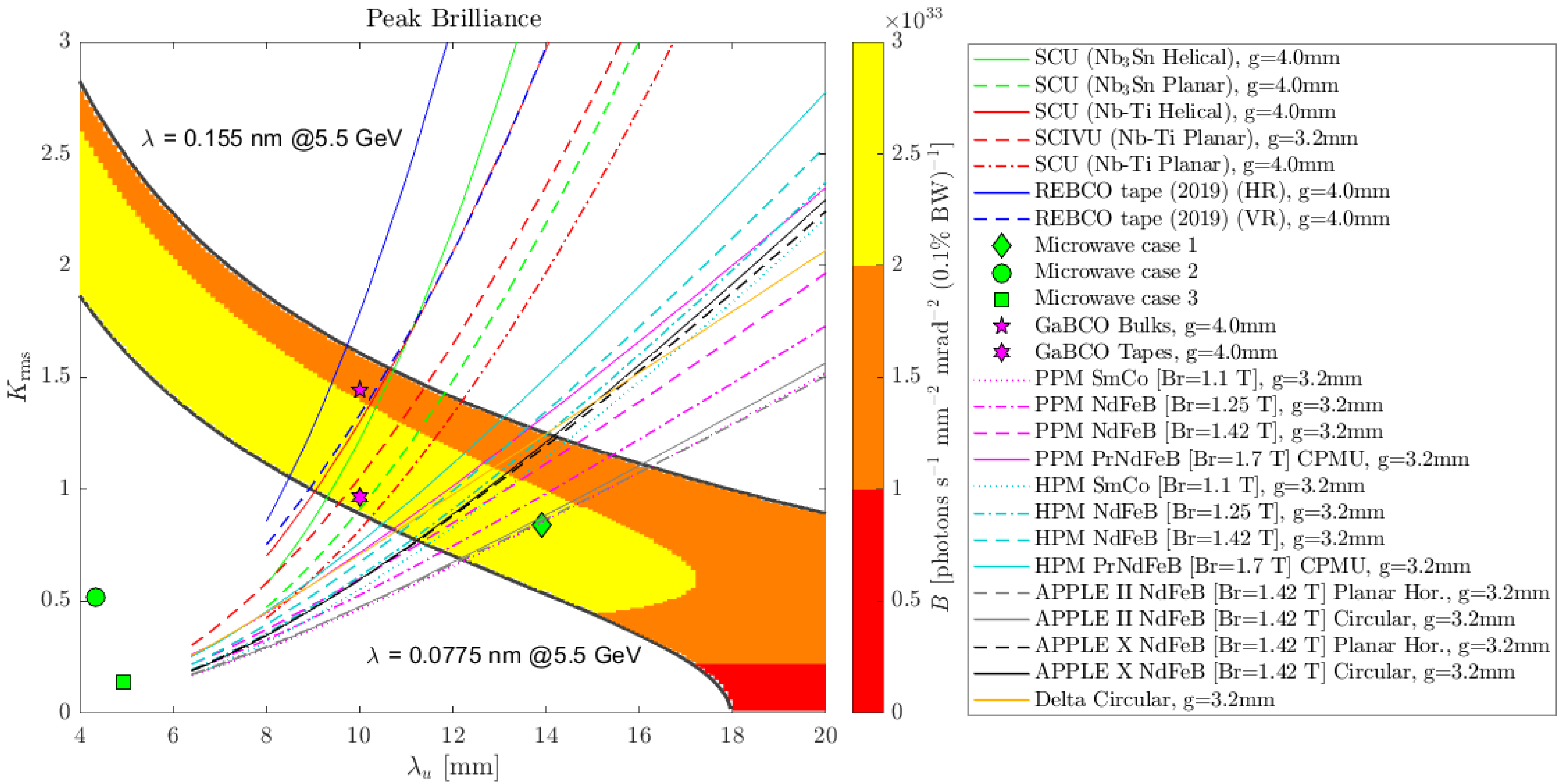
- All merit functions continue to increase with higher beam energy

Peak Brilliance *B* @ 4.5 GeV



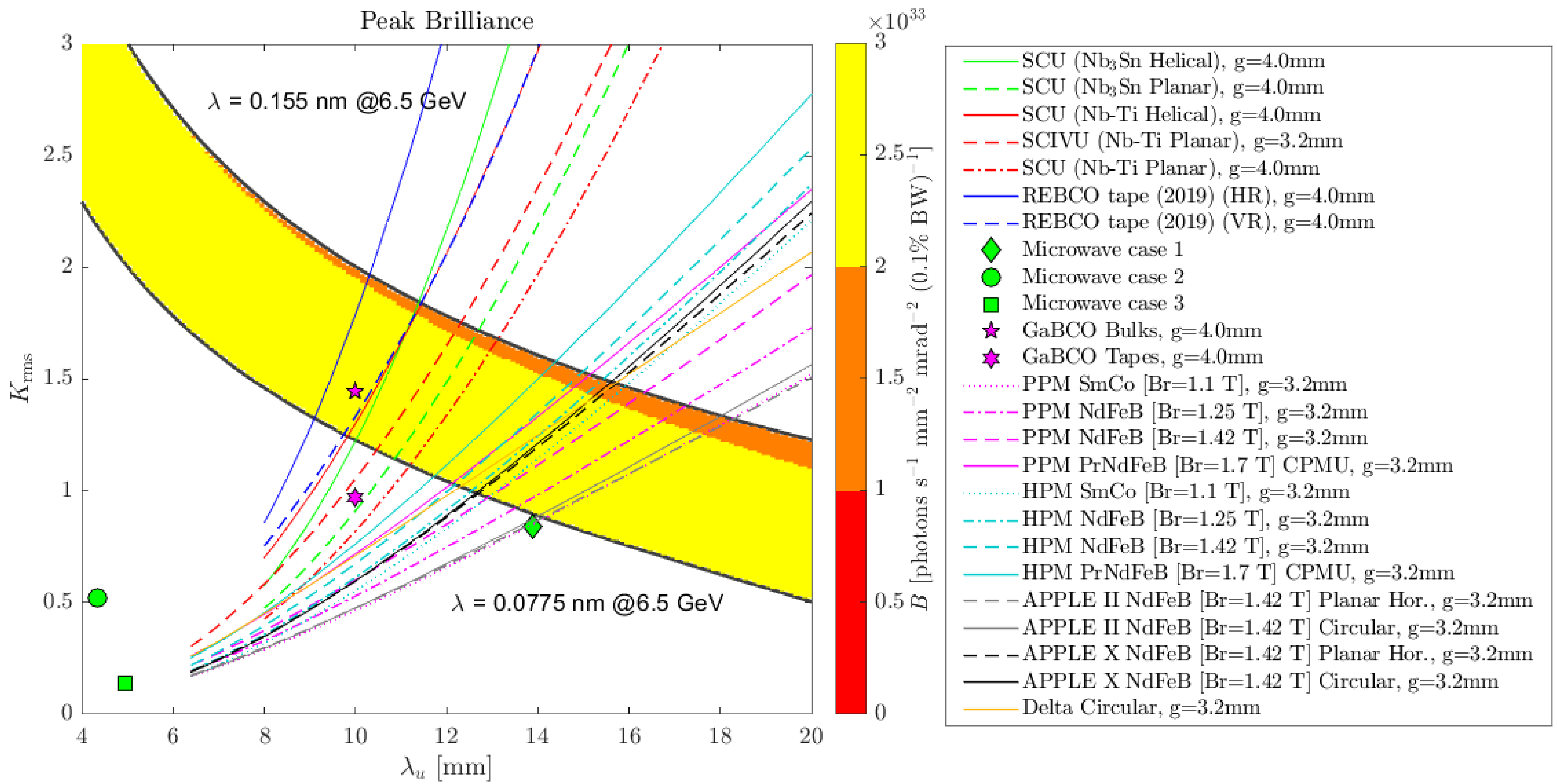
- ‘Weakest’ undulators can’t reach 0.0775nm wavelength
- No undulator achieves threshold brightness

Peak Brilliance *B* @ 5.5 GeV



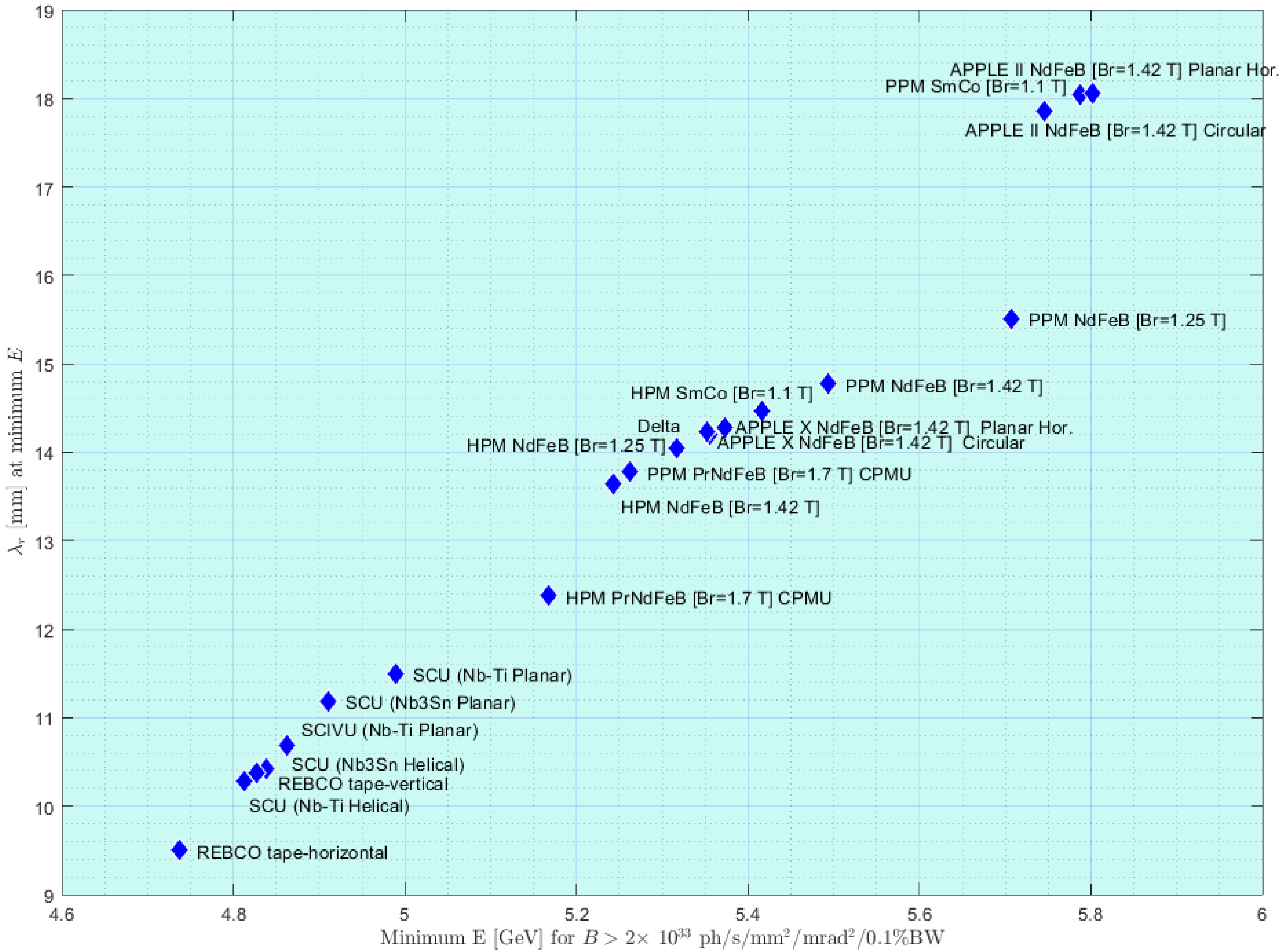
- Most undulators achieve threshold brightness
- Higher energy gives higher brightness

Peak Brilliance *B* @ 6.5 GeV



- All undulators achieve threshold brightness
- Stronger undulators achieve higher brightness
- Higher energy gives higher brightness

Min. E for B > $2x10^{33}$ (ph/s/mm²mrad²/0.1%BW)



Special case: Microwave case 2

- Don’t have data for all periods, so shown on previous plots as single point - ***clearly an outlier***
- The maximum K_{rms} = 0.52 (at period 4.34mm) therefore the tuning range is not a factor of two: $(1+K^2) = 1.25$. This means energy tuning would be required
- But how would the performance compare with the REBCO tape (HR) which seems the strongest contender otherwise?

	REBCO tape	**Microwave 2**	**Microwave 2 /REBCO**
Period	9.7 mm	4.34 mm	
K	0.97	0.52	
Beam Energy	5.5 GeV	3.04 GeV	55%
P_{sat}	23.3 GW	7.3 GW	31%
L_{sat}	13.6 m	10.5 m	77%
B (ph/s/mm^2/mrad^2/0.1%BW)	2.7e33	9.6e32	35%
B/L_{sat}	1.9e32	9.1e31	47%

- Therefore if we used a microwave undulator instead of REBCO:
  - we would save 2.5GeV (or ~40m of linac and building assuming 65MV/m) but only 3m of undulator.
  - the peak brightness would be reduced by a factor of three, to below the user specification, but ***could be recovered*** via tapering, or increasing peak current, or self-seeding.......

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Conclusion

- **The full study and reassessment, based on the complete set of undulator parameterisations, confirms the earlier initial study:**
- Choose nominal beam energy of ***5.5 GeV***
- This is ***lower than SwissFEL*** (even though photon reach is higher)
- Still allows choice of undulators
- ***Also note*** that undulator technologies with strongest fields
  - allow E < 5.5GeV,
  - ***or*** give better performance at 5.5GeV,
  - ***or*** some combination of both
- The most exotic technologies, for example Microwave 2, would allow a large reduction in beam energy (hence facility size, cost) with a level of performance reduction that might be acceptable and is potentially recoverable.

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Thank you!

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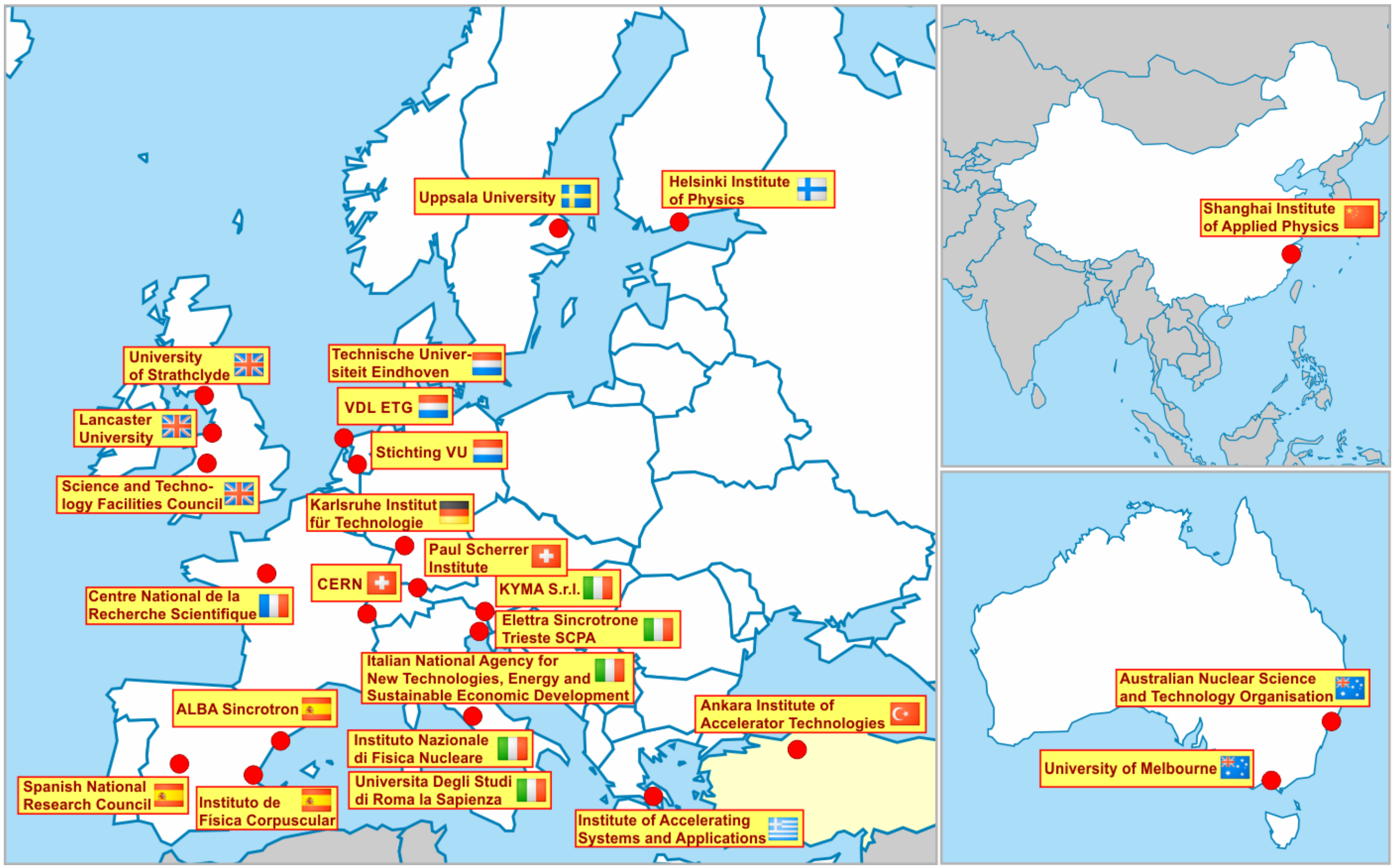

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