WP5: Update on Undulator Options

Neil Thompson, STFC, 17/06/20

Introduction

- The original assessment was that for best performance in the HXR (up to 16keV) we should use a helical Superconducting Undulator (SCU) with a period of 11mm.
- This was based on studying the performance of different undulator technologies.
- For WP5 Deliverable 5.1 the decision was made to relax the period slightly to 13mm, to allow a little margin, and adjust the undulator a_w range accordingly.
- In the meantime Vitaliy made calculations of the output in the SXR and found that pulse energies were not competitive with other facilities (for example LCLS). His results were consistent with Genesis simulations in the SXR.
- Partly this is expected – for example we have a lower bunch charge and beam energy than LCLS, both of which will affect the FEL pulse energy.
- Nevertheless, it was agreed to re-assess the undulator parameters to answer the question:

Have we been too concerned with the FEL output at 16keV to the detriment of the SXR, and can we 'rebalance'?

- This talk shows the results. I have looked at three variables – **minimum gap**, **tuning range** and **undulator period** – to illustrate the impact they have and see what improvements could be made.
- I have also compared the optimum SCU option with a non-superconducting technology (APPLE-X) to confirm the benefits

Introduction

- Here have assumed a helical SCU with parameterisation given in D5.1

$$B(\lambda_u[\mathrm{mm}], g[\mathrm{mm}]) = c_1 \cdot (c_2 + c_3\lambda_u - c_4\lambda_u^2 + c_5\lambda_u^3)\exp\left(-\pi\left(c_6\frac{g}{\lambda_u} - 0.5\right)\right). \qquad a_w = K = \frac{eB_0\lambda_u}{2\pi mc}$$

where $B_0 = B_{x_0} = B_{y_0}$ is the peak field in each plane.

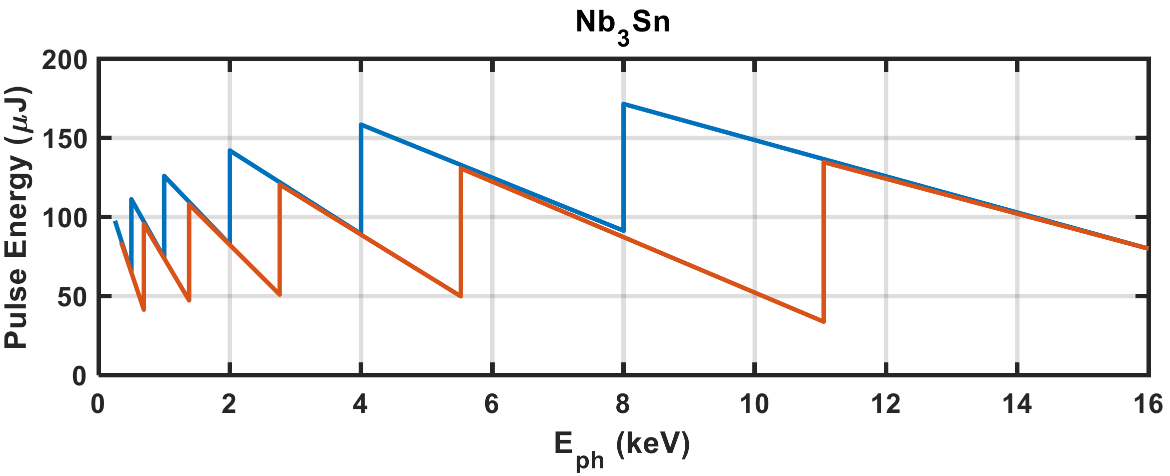
	Nb-Ti		Nb_3Sn	
	Planar	Helical	Planar	Helical
c_1	1.17	1.70 ± 0.15	1.3	1.25 ± 0.12
c_2	0.28052	0.055 ± 0.013	0.28052	0.04 ± 0.05
c_3	0.05798	0.063 ± 0.005	0.05798	0.056 ± 0.018
$c_4/10^{-4}$	9	25 ± 3	9	-10 ± 20
$c_5/10^{-6}$	5	51 ± 12	5	-30 ± 80
c_6	1	0.8333 ± 0.0015	1	0.940 ± 0.006
λ_u/g	0.5	0.5	0.5	0.5

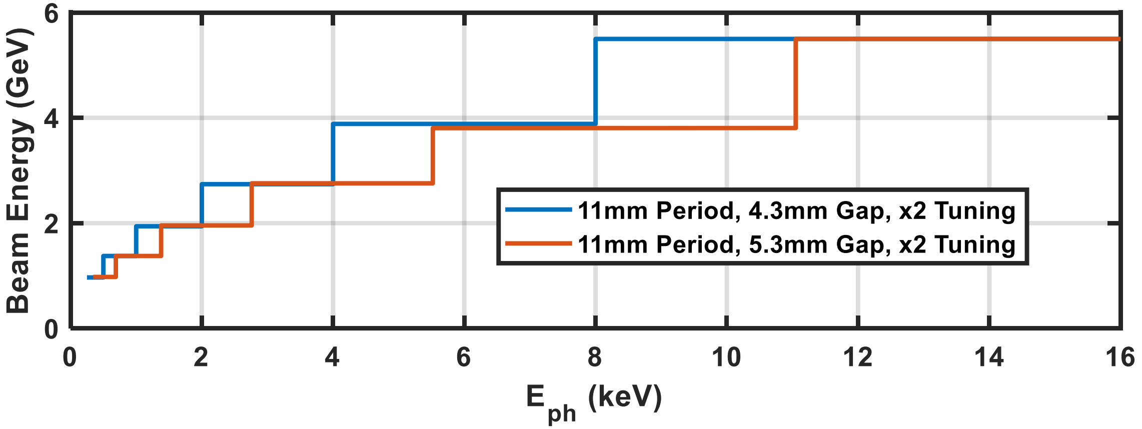
- Most calculations use the Ming Xie parameterisation with a 'filling factor' of FF = 0.6 used when calculating pulse energies from peak powers (to account for SASE spikiness).
- Some results cross checked with Genesis1.3
- The initial constraint assumed is that the maximum beam energy is 5.5GeV

Funded by the
European Union

Effect of Minimum Gap Choice (NbSn)

Compact



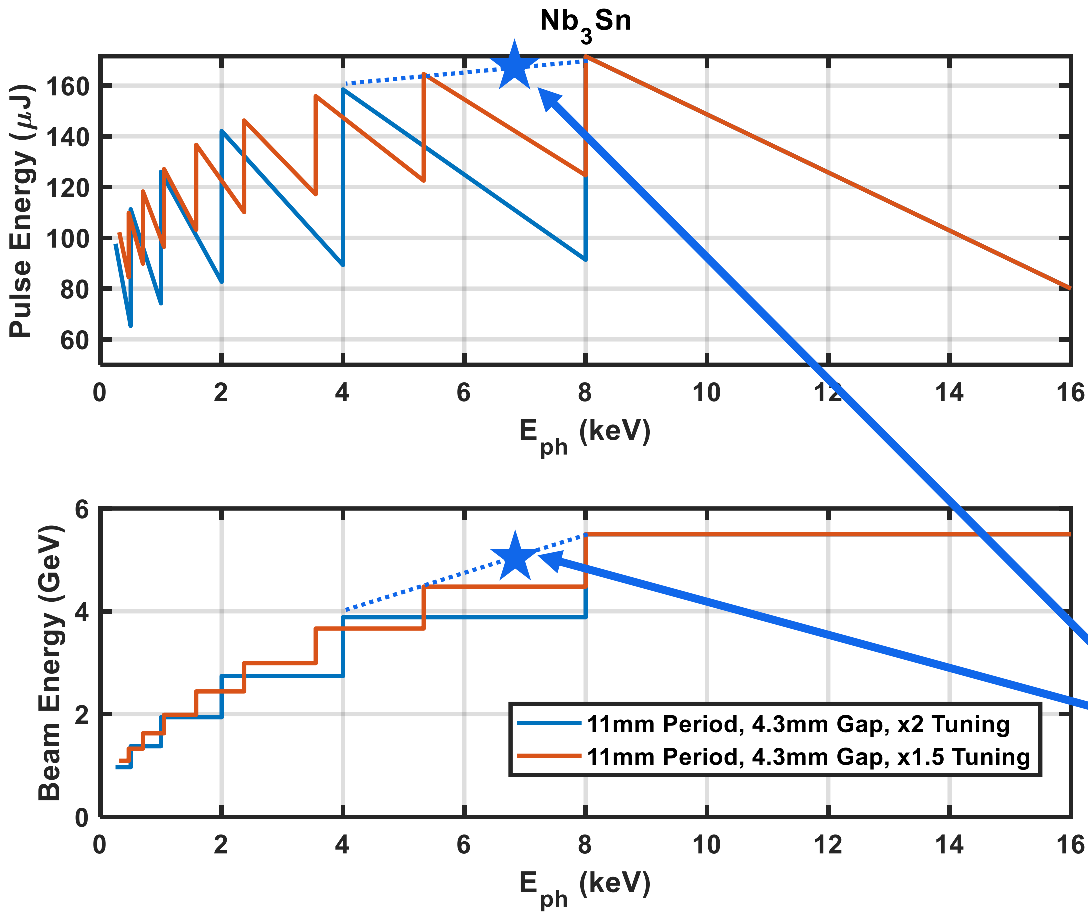


- Tuning range factor of two where possible.
- Gap choice makes no difference to output at 11-16keV (same period, aw, beam energy)
- At E_{ph} < 11keV output is better for 4mm gap – higher aw and beam energy available.

A gap of 4.3mm gives on average about a 15% increase in pulse energy compared to using a 5.3mm gap (for the same period). Zafer's results indicate increased wakefield losses acceptable.

Funded by the
European Union

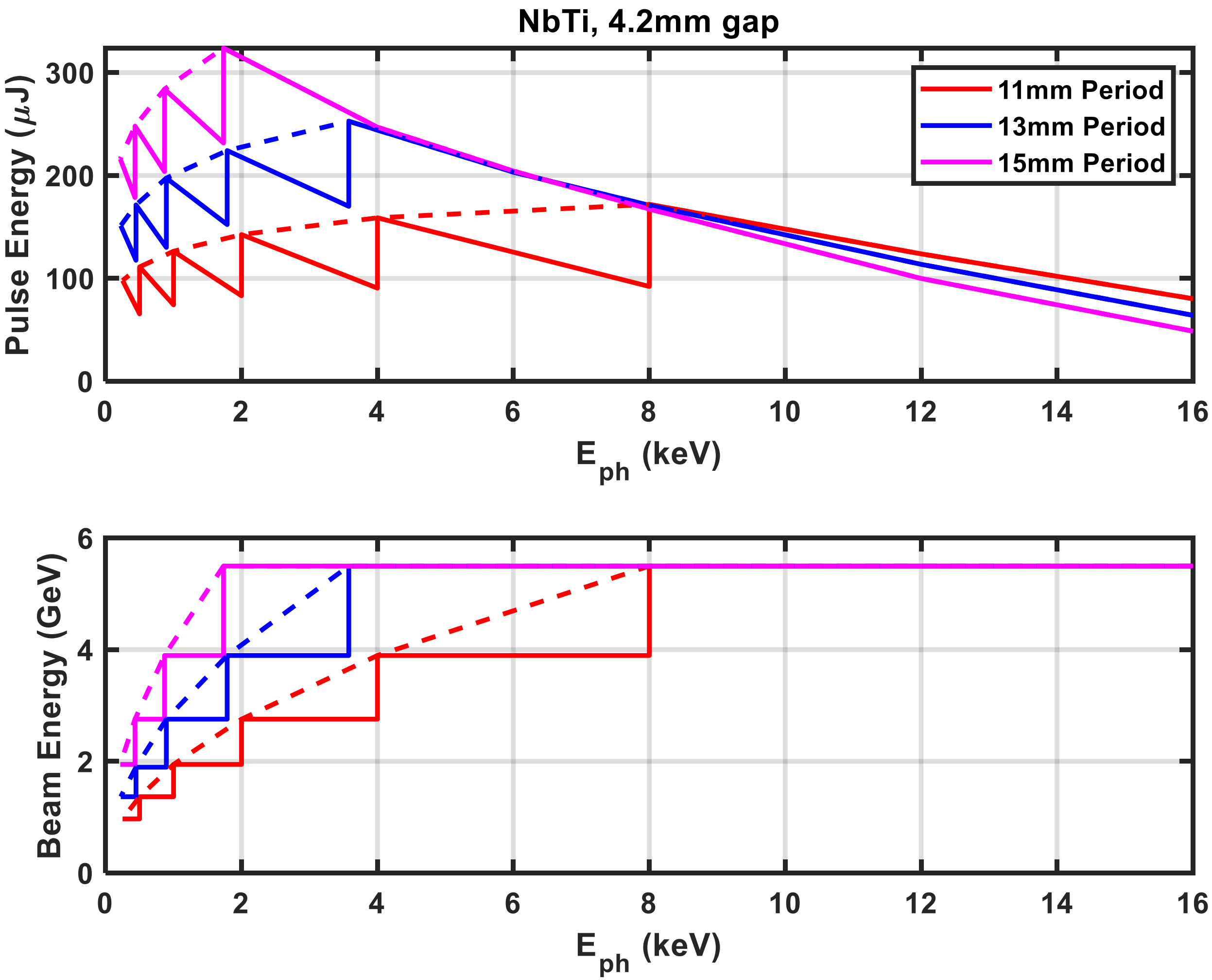
Effect of Tuning Range Choice – X2 vs X1.5



- ***No difference*** from 8 – 16keV
- For E_{ph} < 8keV pulse energies higher on average because minimum a_w is higher and beam energy is higher
- BUT need more beam energies to cover wavelength range so less practical

If a particular experiment at <8keV wanted maximum pulse energy we could always operate at the optimum beam energy and a_w for that wavelength – in this case the nominal tuning range is irrelevant.

NbTi, 4.2mm gap: Effect of Period Choice –
X2 tuning range where possible, 4.2mm gap



HOWEVER:

THERE IS A LIMIT ON THE MAXIMUM BEAM ENERGY FOR SXR OPERATION @ 1kHz

1khZ Beam Energy Considerations

- **From Walter**: "*For the exact energies of the different cases, there are some more levels of precision. The first is a detail of the rf pulse compression change due to different klystron pulse length. The exact numbers for energy gain per module can be found on Marco Diomede's presentation at the annual meeting https://indico.cern.ch/event/867582/timetable/#20200121.detailed, slide 13. In addition there was some discussion during the Athens meeting about off crest acceleration (needed for short-range longitudinal wakefield compensation), which changes along the length of the linac, so there are further corrections to the exact energies. The accounting of the number of modules is being taken care of by Avni, Markus and Carlo, consistently I hope! All that together would give you the HXR and SXR energies. I start to wonder how close the numbers are to those you give in the facility overview slides. It should all be double checked.*"

	Rep. rate [Hz]		
	100	250	1000
Average gradient <G> [MV/m]	65	32	30.4
Max klystron available output power [MW]	50	50	10
Required input power per module P_K [MW]	39	42.5	8.5
RF pulse [μs]	1.5	0.15	1.5
SLED	ON	OFF	ON
Av. diss. power per structure [kW]	1	0.31	2.2
Peak input power per structure [MW]	68	10.6	14.8
Av. Input power per structure [MW]	44	10.6	9.6
Module energy gain [MeV]	234	115	109

120 140 160 180

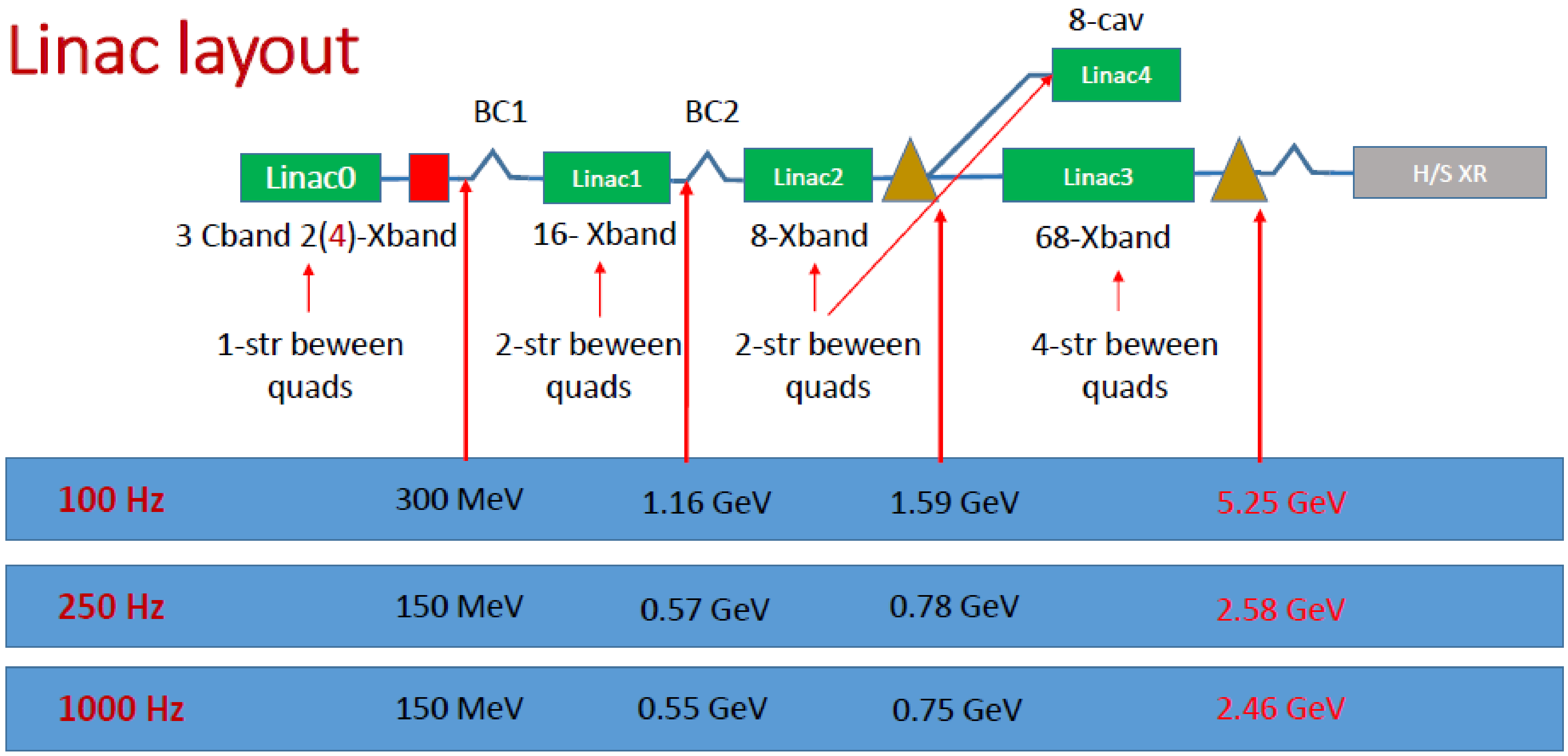
Soft X-rays:
L0 gradient = 19.8 MV/m; phase = 24.0 deg
L1 gradient = 10.9 MV/m; phase = 15.5 deg
L2-3 gradient = 10.4 MV/m; phase = -23.4 deg
Ka-band gradient = 8 MV/m; phase = 201 deg
BC1 angle = 3.18 deg; BC1 angle = 2.12 deg

ry 2020 – Athens A. Latina 6

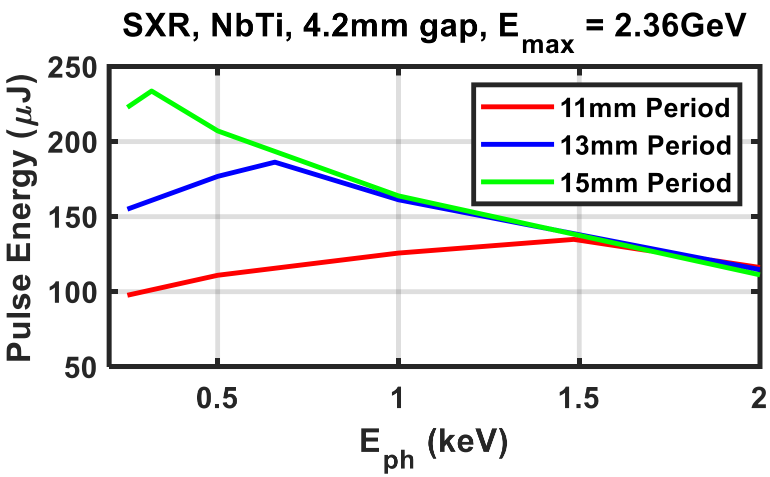
Therefore estimate max energy at 1kHz: 5.5GeV * 109/234 * cos(23.4 deg) = 2.35GeV

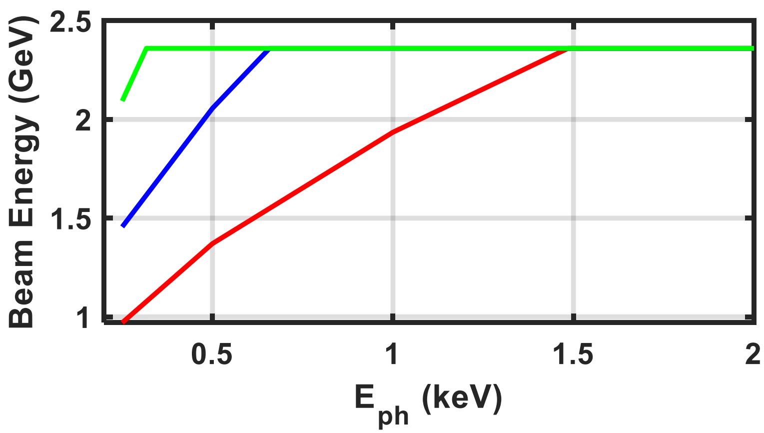
Rep. Rate [Hz]	Module crest gain [MeV]	Linac1 gain (67 deg) 4 modules [MeV]	Linac2 gain (67 deg) 2 modules [MeV]	Linac3 gain (67 deg) 17 modules [MeV]
100	234	861.6	430.8	3661.8
250	115	423.4	211.7	1799.6
1000	109	401.3	200.7	1705.7

Linac layout

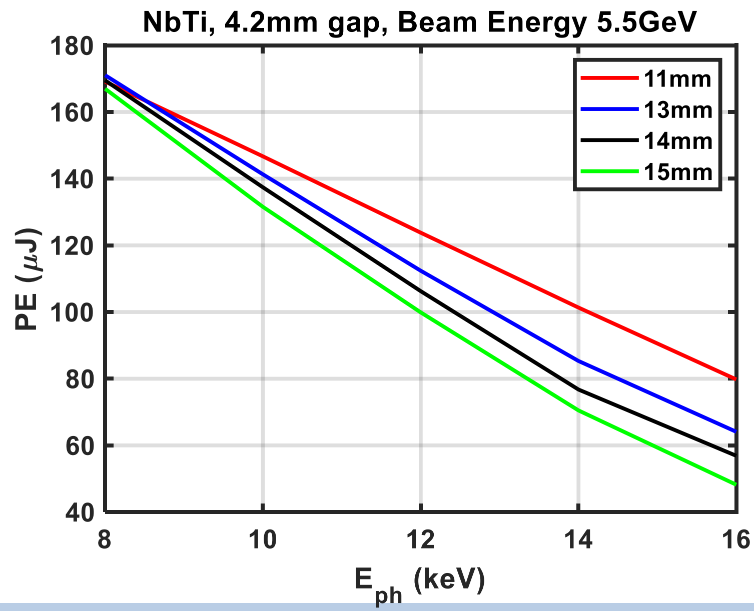


SXR: 0.25 – 2.0 keV

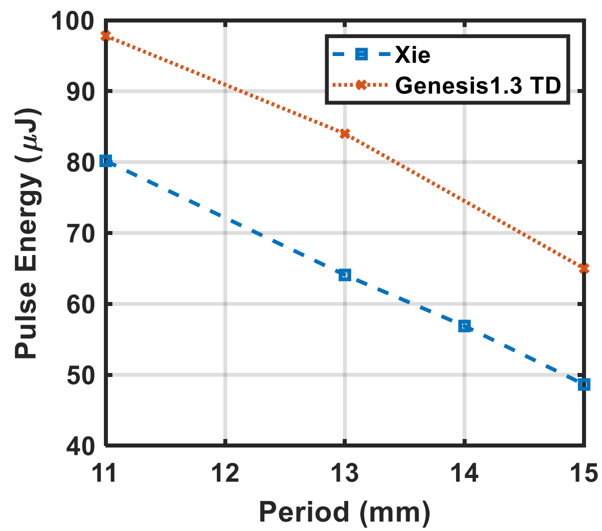


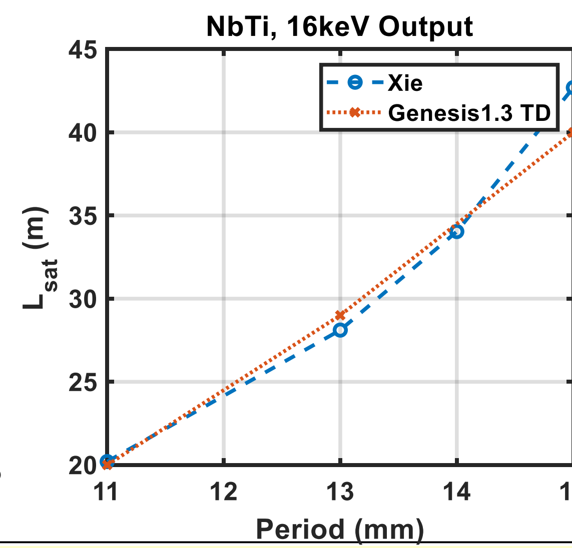


HXR: 8 – 12 keV

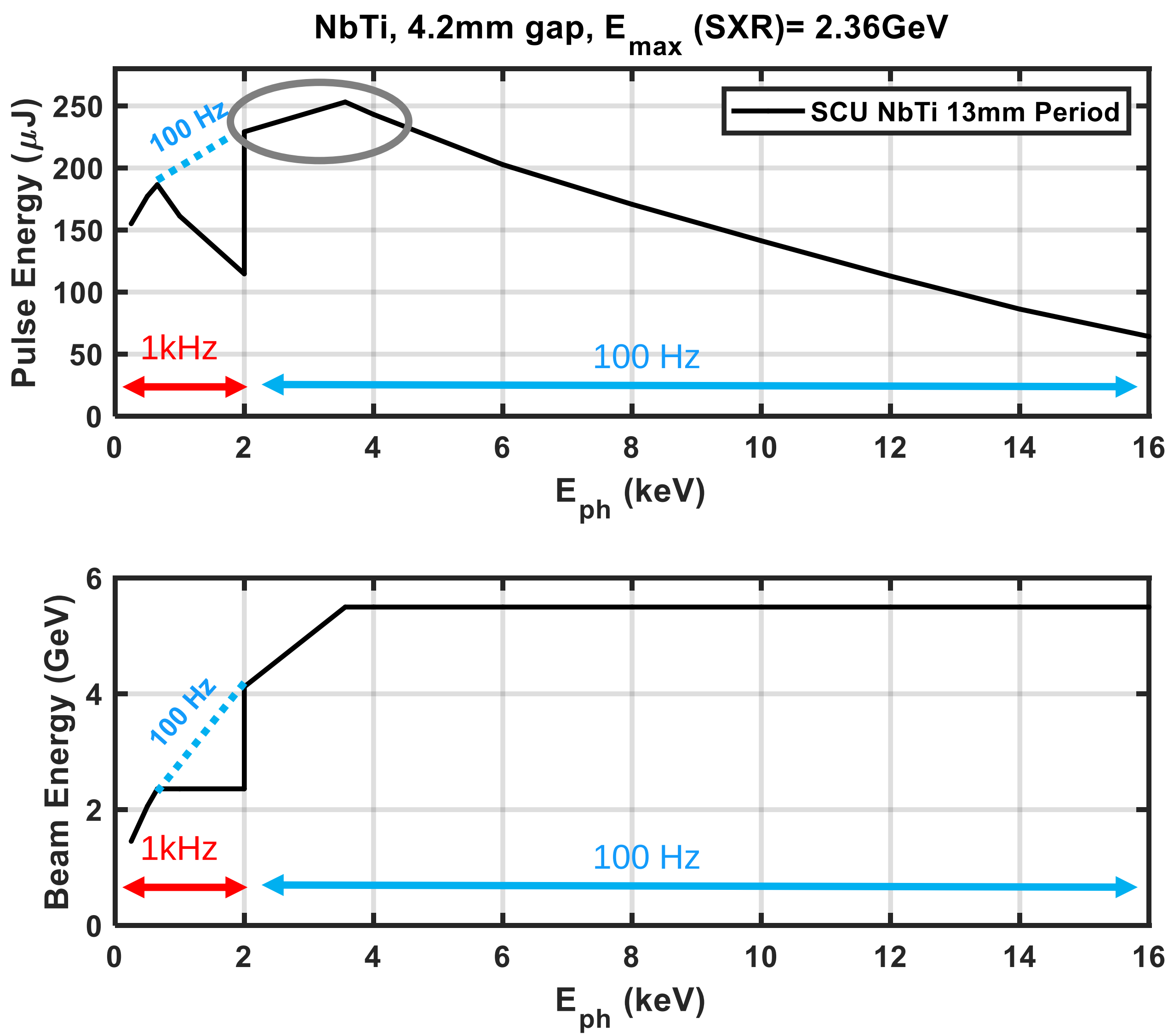


HXR: 16 keV – Xie *vs* Genesis1.3



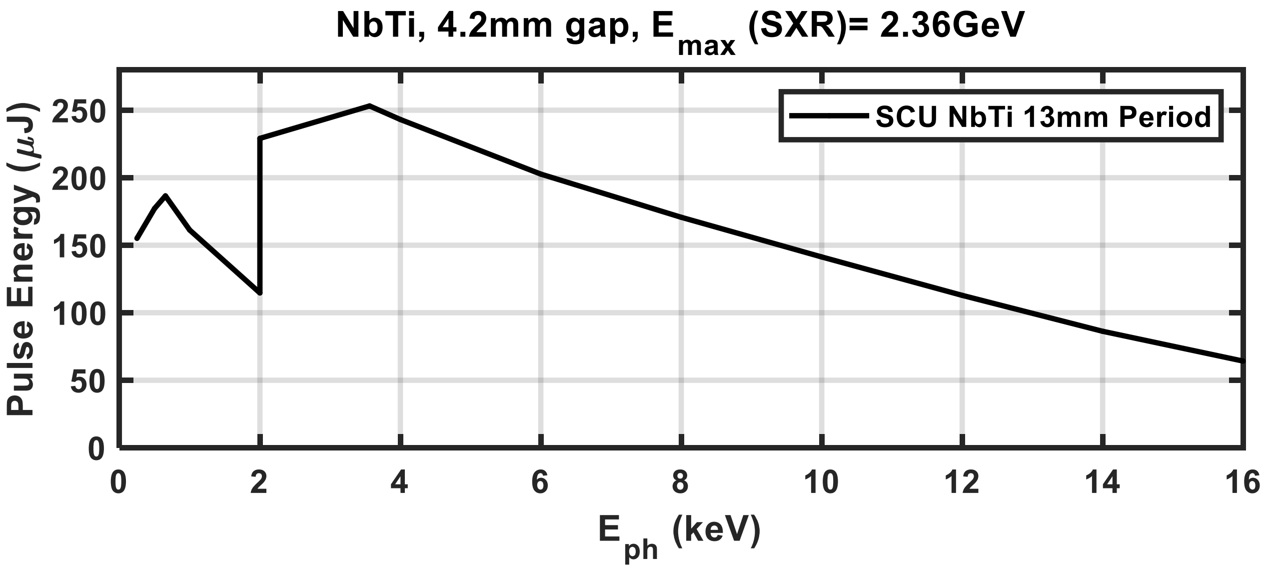


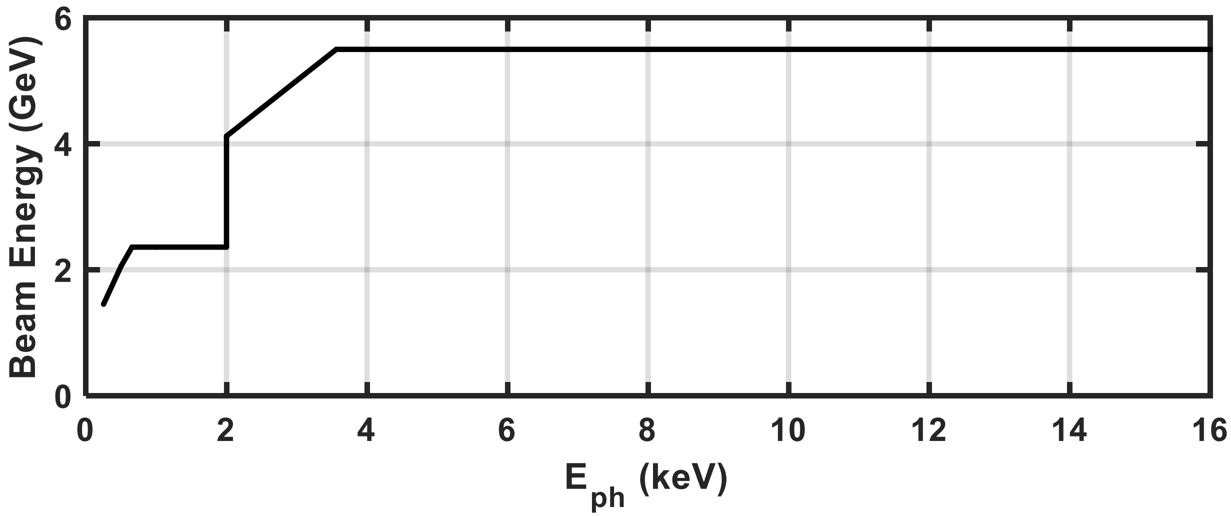
13 mm SCU Max Pulse Energy vs E_{ph}



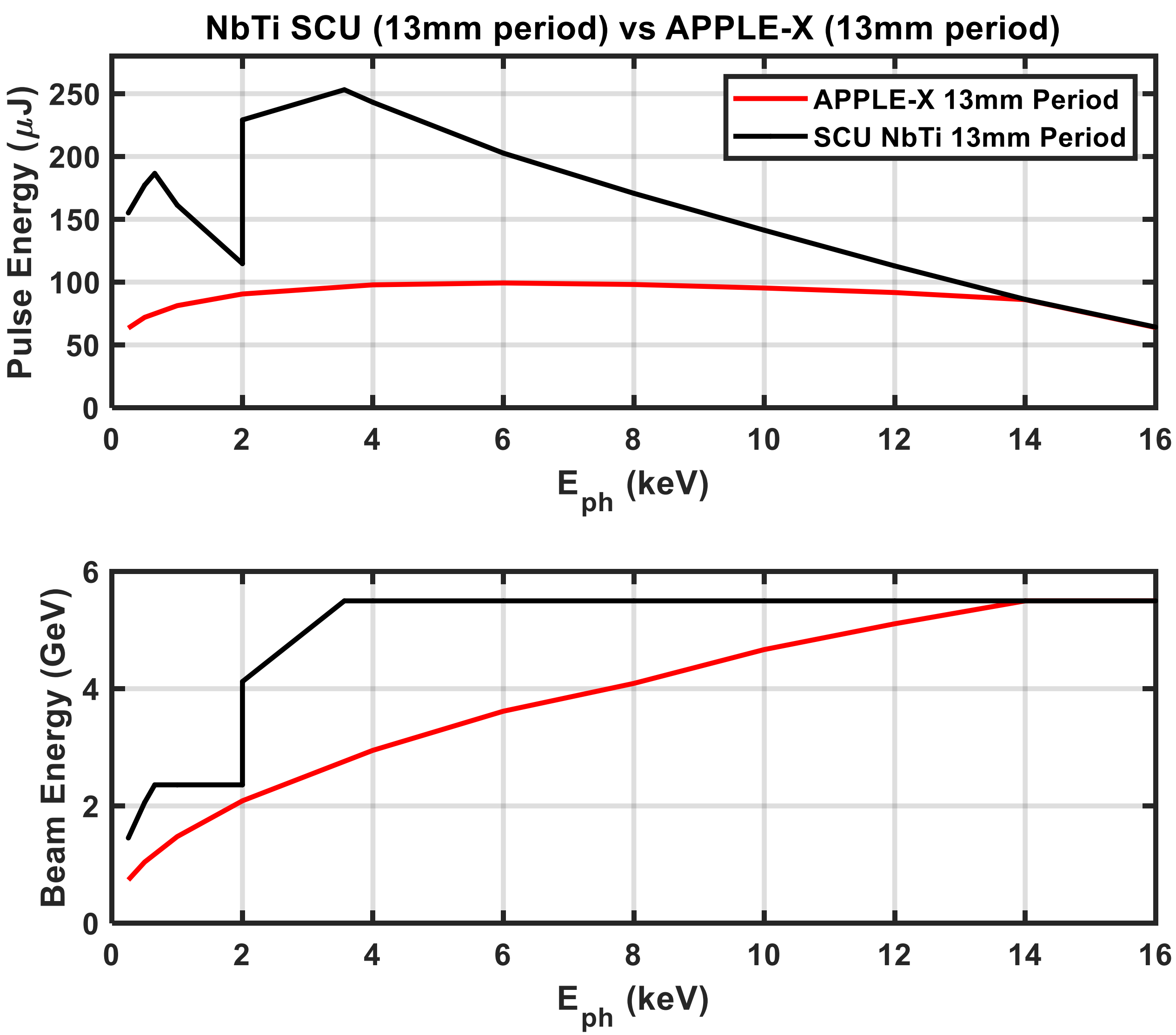
N.B. Peak photon energy in 2-4keV range: this region (tender X-rays) is still not well covered by other FEL facilities and there is an increased interest from users in this region.

(At LCLS -I they even had a gap from 3 to 5 keV because the main effort was on the higher energy operation)

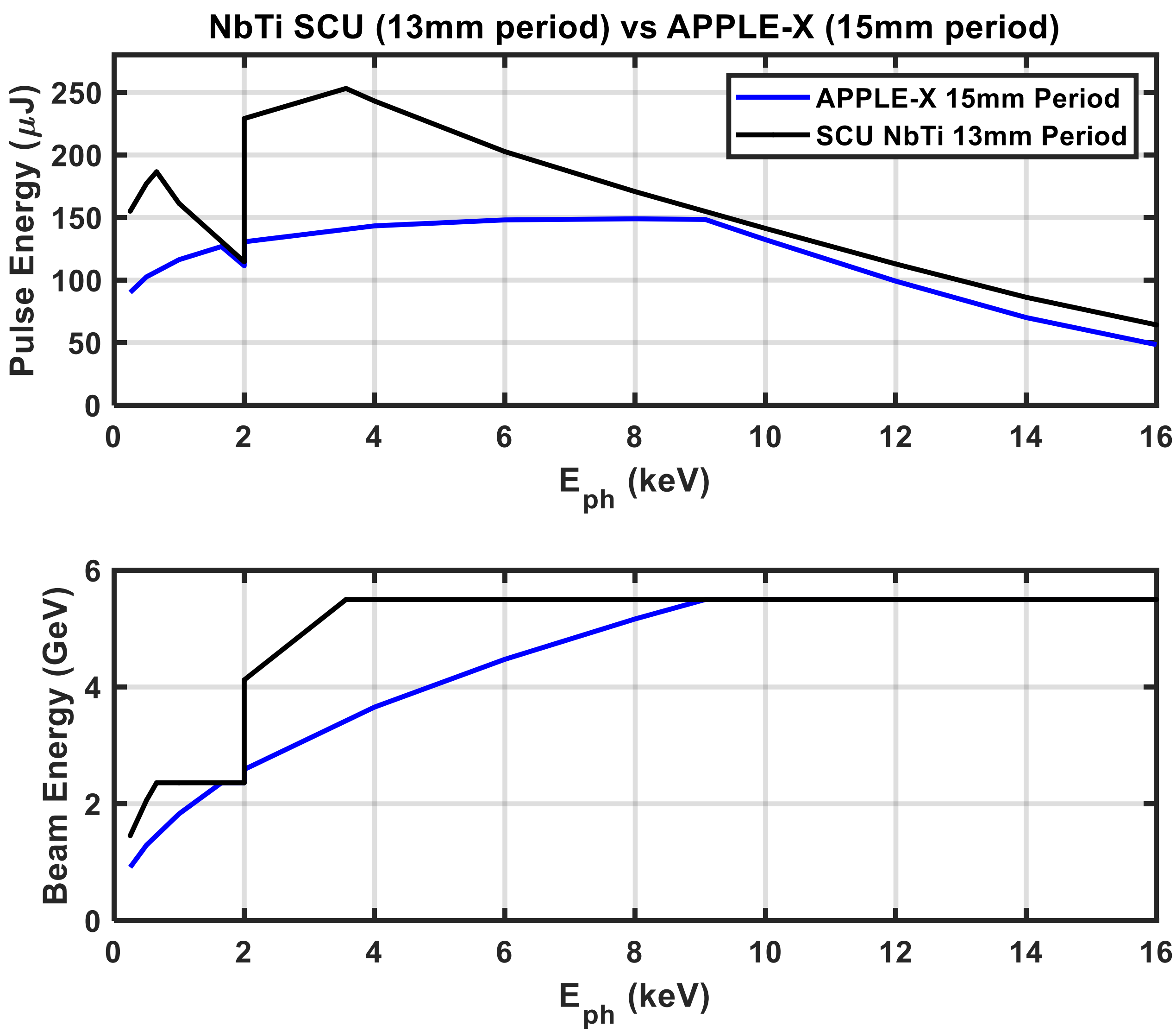

NbTi, 4.2mm gap, E max (SXR)= 2.36GeV
SCU NbTi 13mm Period
Pulse Energy (μJ)
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
E ph (keV)


Beam Energy (GeV)
6
4
2
0
0
2
4
6
8
10
12
14
16
E ph (keV)

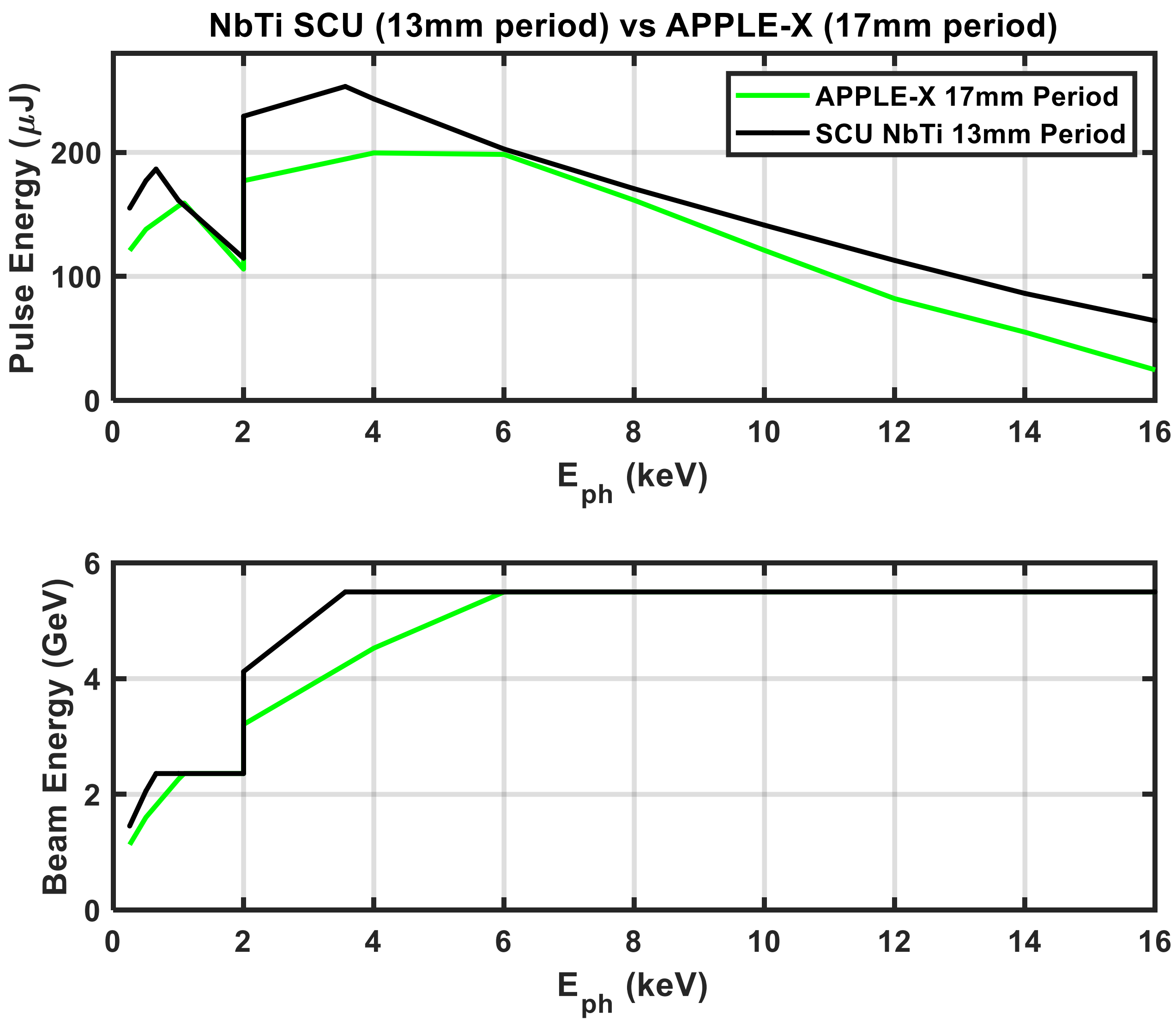
SCU (13mm) vs APPLE-X (13mm)



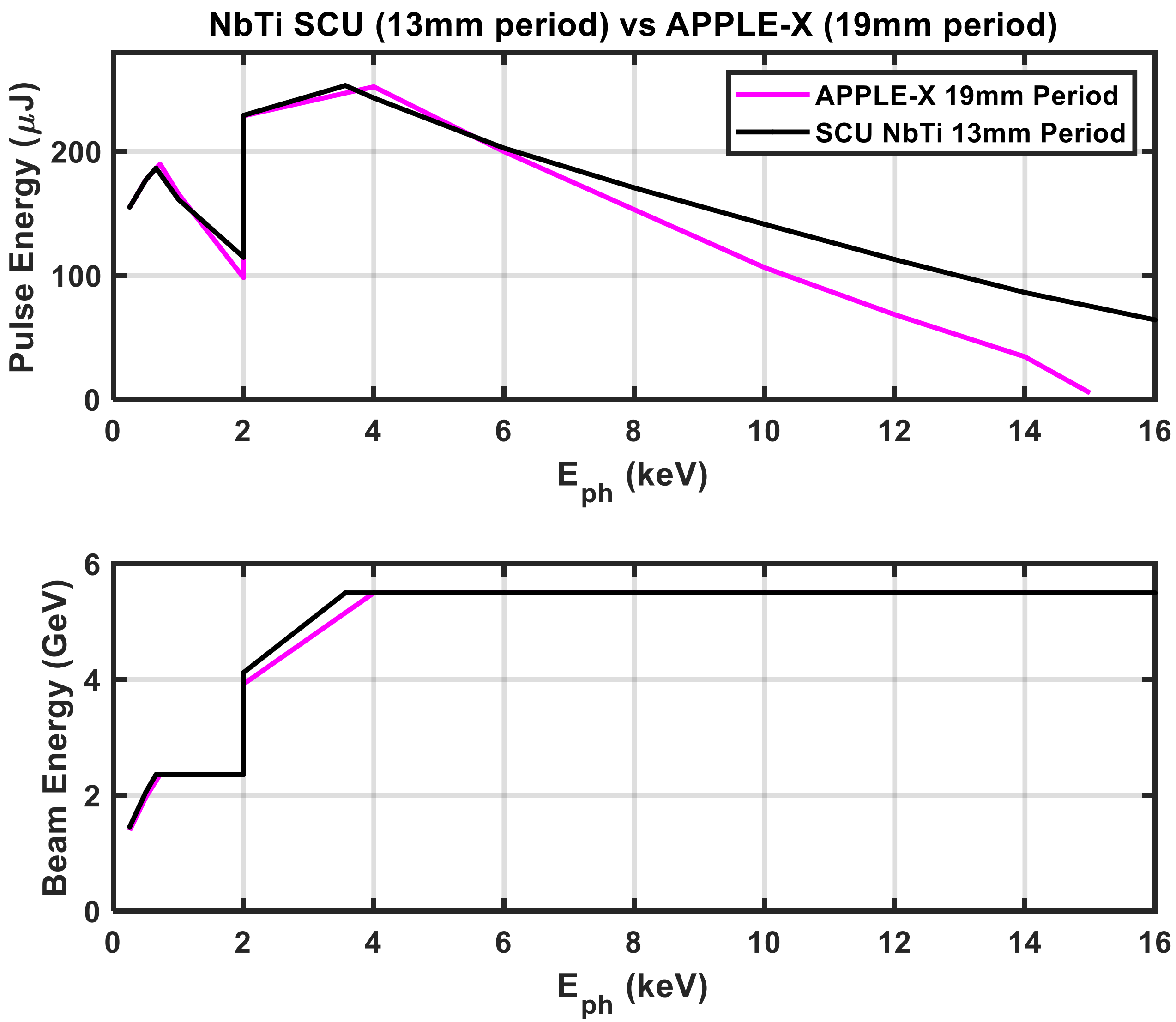
SCU (13mm) vs APPLE-X (15mm)



SCU (13mm) vs APPLE-X (17mm)



SCU (13mm) vs APPLE-X (19mm)



Conclusion

- The original SCU period of 11mm does give the best performance in the HXR from 8-16keV.
- An SCU period of 13mm gives a ***more balanced*** performance across the whole wavelength range, notably about double the pulse energy in SXR
  - 15mm gives too long saturation length at 16keV, and better performance in SXR ***only in the range 0.25 – 0.65keV***
  - 11mm gives marginally better performance from 8 – 16keV
- The tuning range by adjusting the undulator field strength is only a matter of convenience – it doesn't limit the potential performance at any photon energy.
- Minimum gap of 4.2mm gives better performance than 5.2mm, balanced against the increased wakefield degradation.
- It is not possible to find a period for an APPLE-X undulator that matches the performance of the SCU across the whole photon energy range.
- The SCU is the best choice for a facility such as CompactLight where we wish to use the same undulators for SXR ***and*** HXR

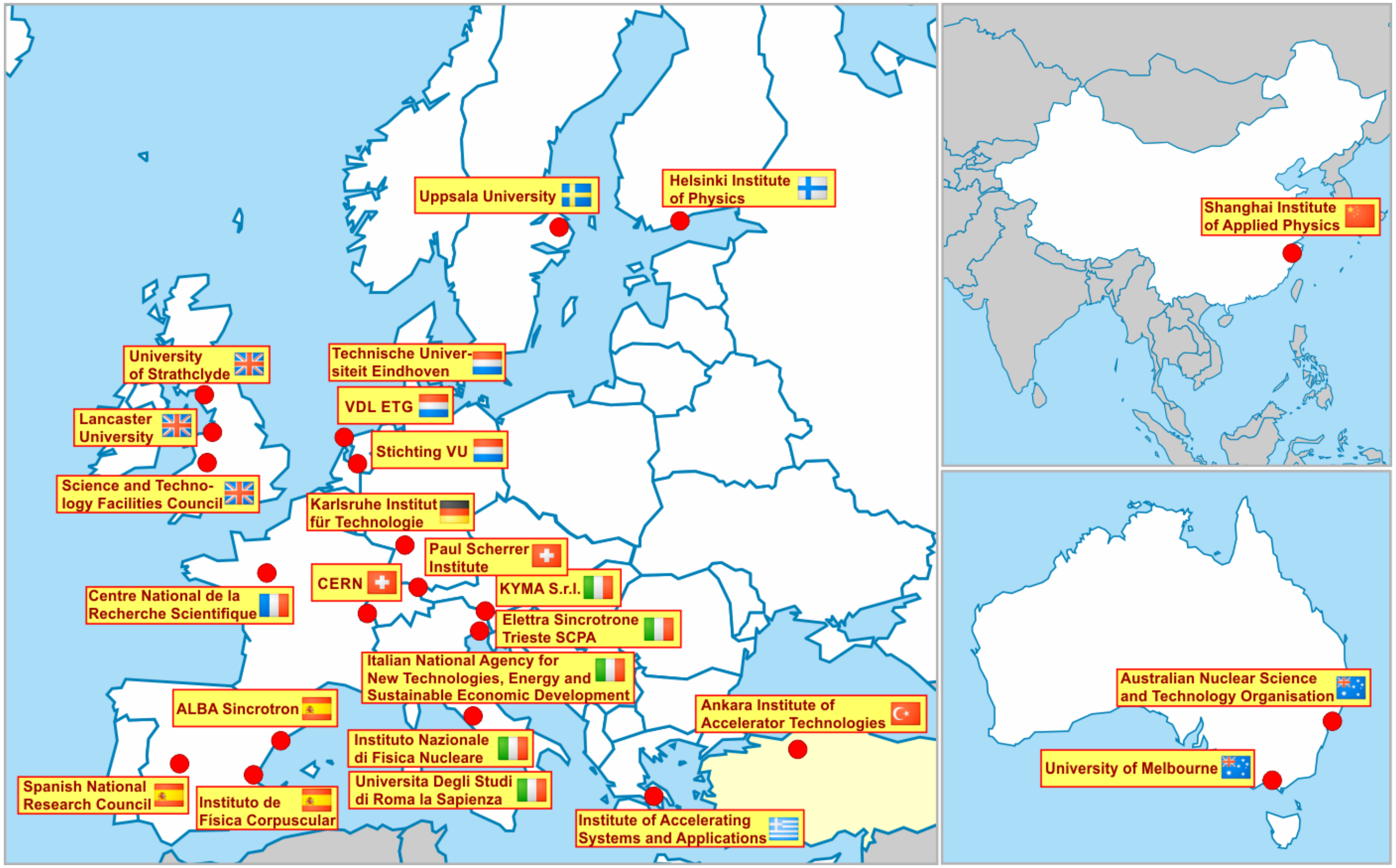
Funded by the
European Union

Compact

Thank you!

CompactLight@elettra.eu

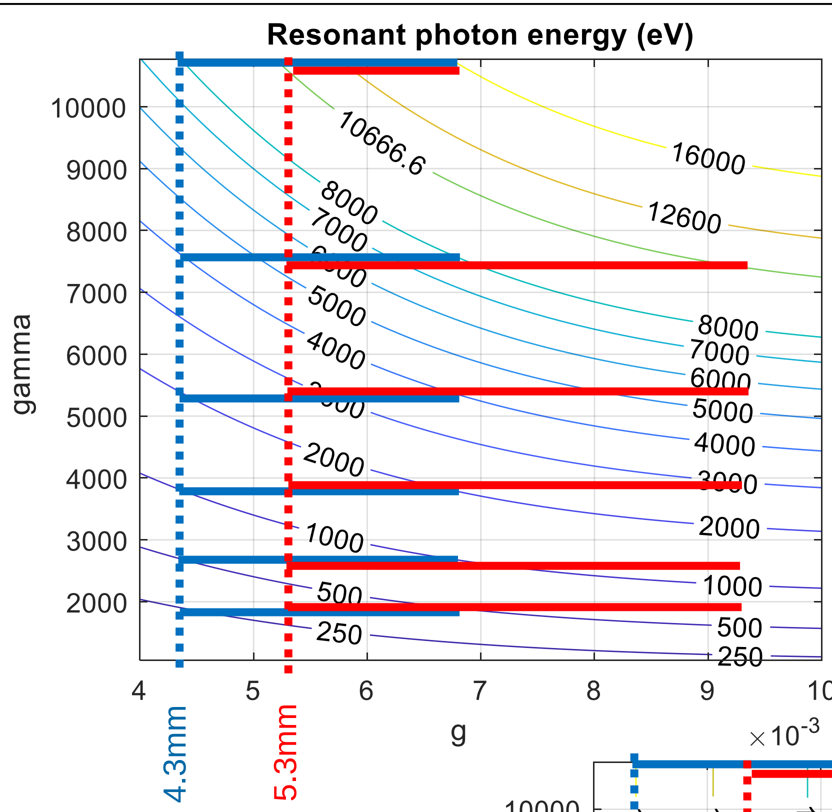
www.CompactLight.eu

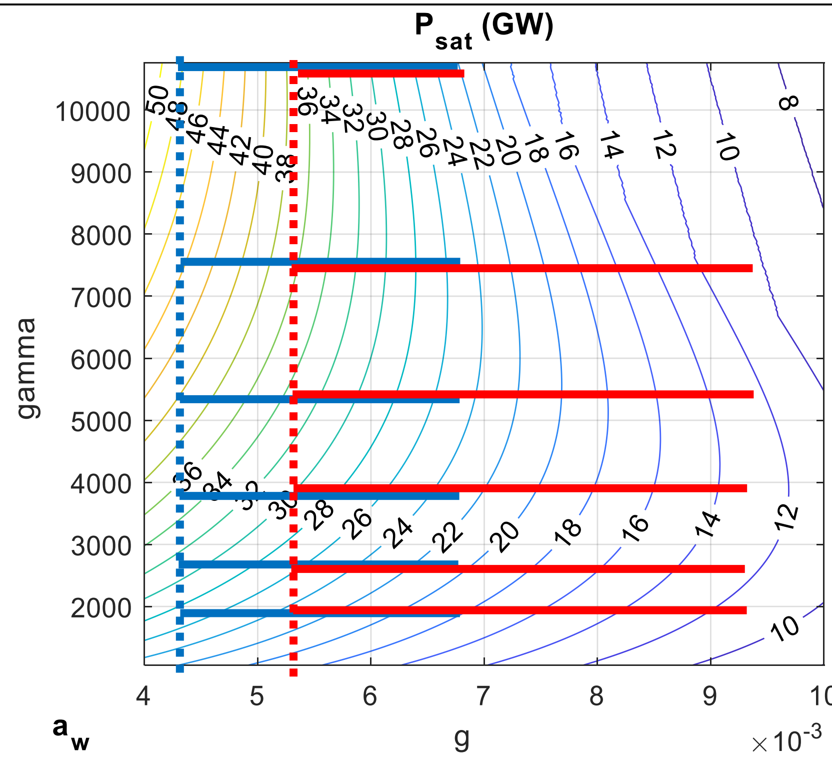


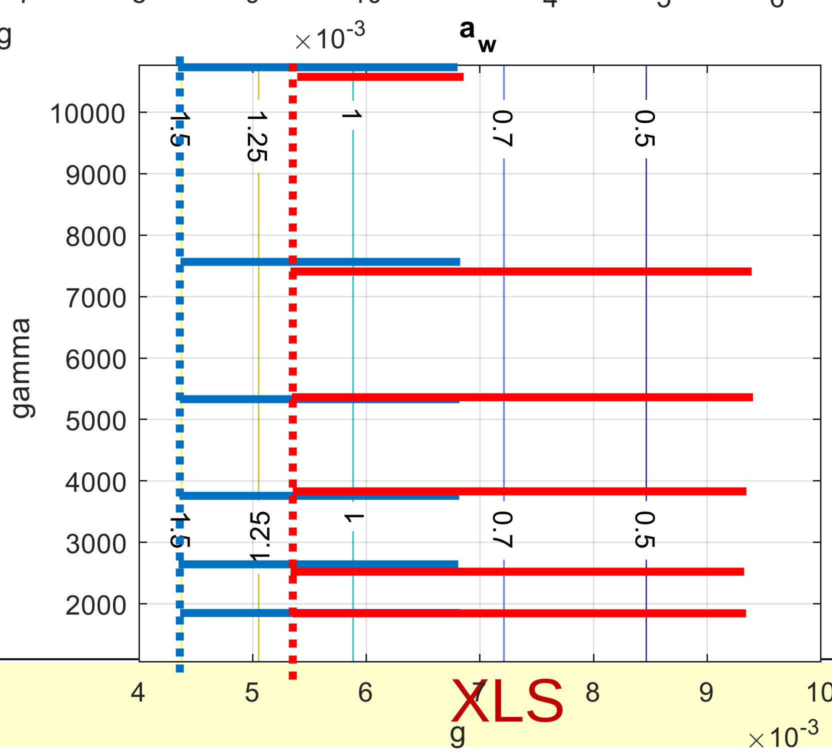
CompactLight is funded by the European Union’s Horizon2020 research and innovation programme under Grant Agreement No. 777431.

Extra……

Effect of Minimum Gap Choice: Data Source







5.3mm gap

4.3mm gap

NB on these plots gap (g) is proxy for SCU current