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Accelerators in a new light

Compact 

Polarisation and multicolour feasibility within the Soft X-Ray regime

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One year review meeting,
Barcelona, Spain

11-12-2018

- Motivation
- Fixed gap and fixed beam energy approach (1 line)
 - Multicolour
- Fixed gap and fixed beam energy approach (2 lines)
 - Multicolour
- Beam energy tuning (1 lines)
 - Multicolour
- Conclusions and Outlook

List of possibilities

Option	# undulator lines	Tuning method	Undulator period [cm]	Maximum gap [mm]	Electron beam energy
1	1	Gap tuning	3.8	>17	4 GeV (fixed)
2	2	Gap tuning	2.6/3.6	10	4 GeV (fixed)
3	1	Energy tuning	2.0	3	1.3-5 GeV (variable)

- **Option 1 – problem with large gap range?**
- **Option 2 – suitable if ok with 2 undulator lines**
- **Option 3 excluded due to energy tuning?**
- **Additional option (Tunable Energy + tunable gap)**

User requirements

Photon energy variation corresponding to three different wavelength domains:

	Soft x-ray	Hard x-ray
Photon energy [keV] (min-max)	0.25-2	2-25
Wavelength [nm] (max-min)	5-0.6	0.6-0.05
Repetition rate [Hz]	1000	100
Maximum pulse energy [mJ]	Not specified yet (will be < 1mJ)	1 (at 25 keV only, can be less at other energies) – this is 2.5E11 photons/pulse
Pulse duration [fs]	0.1 – 50	
Polarisation	Variable, selectable	Not specified yet
Two-colour pulses: time separation [fs]	-20 -> +40	
Two-colour pulses: photon energy variation (max. of E2/E1)	2 (270-530eV), 1.2 for the rest of the range	1.1

Wavelength	Photon separation
0.6 nm – 2.33 nm (530 eV)	1.2
2.33 nm (530 eV) - 4.59 nm (230 eV)	2
4.59 nm – 5 nm	1.2

Motivation

<i>Undulator parameters</i>	
undulator period	1.7 cm
undulator gap	3 mm
deflection parameter (RMS)	1.9
<i>Bunch parameters</i>	
beam energy	4 GeV
pulse duration (FWHM)	10 fs
bunch charge	20 pC
peak current	1.9 kA
norm. emittance	0.12 mm×mrad
energy spread	0.01 %
<i>Potential reach</i>	
FEL wavelength ($\hbar\omega$)	0.66 nm (1.9 keV)
N_γ /pulse	5.6×10^{11}
E_{FEL} /pulse	0.2 mJ
saturation length	21 m

Small increase in E_{beam} allows
to reach for 0.6 nm (2 keV)
comfortably

Emittance stays well between
Pellegrini's and Di Mitri's limits

Variable polarization & Two
Colours operations require
careful feasibility studies with
these undulator parameters, in
particular at small period:

H. M. Castaneda Cortes is
tackling this issue in WP5 and
is greatly acknowledged

Please, stay FEL-tuned

- A Ming Xie analysis has been performed with that in mind, looking at saturation length, saturation power for different undulator technologies and different undulator types, following the resonance condition

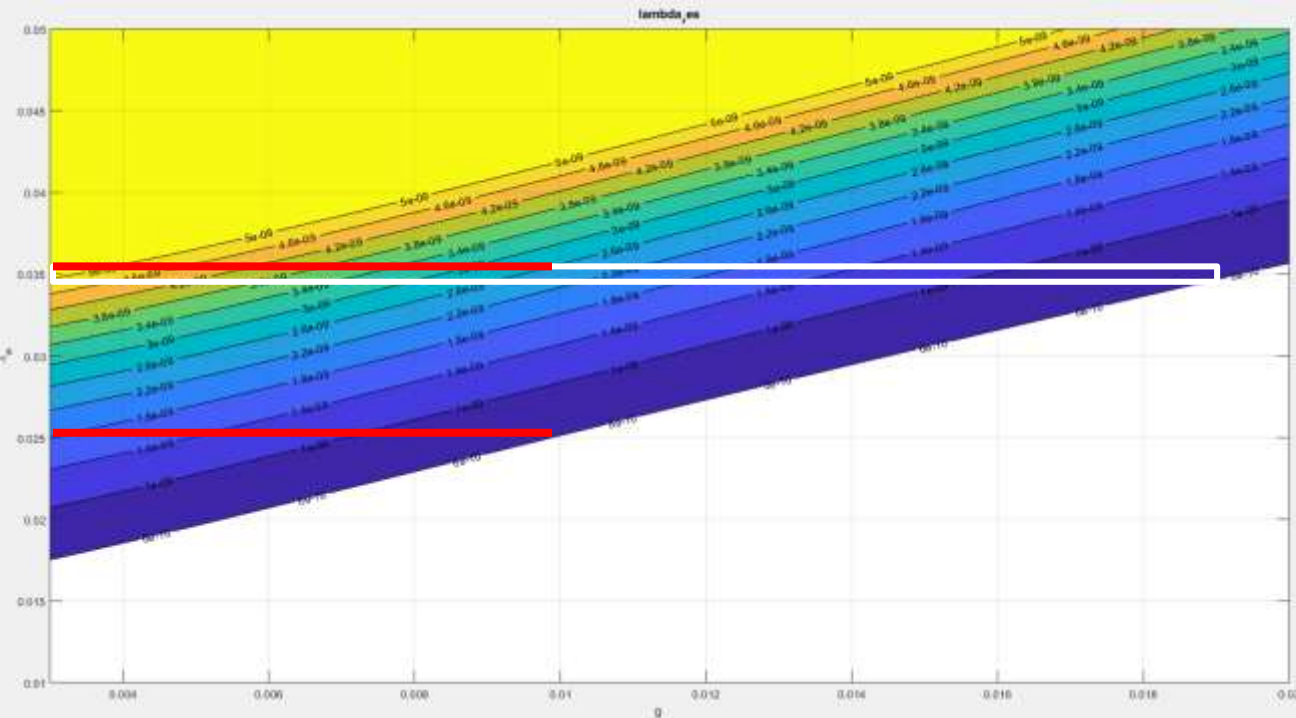
$$\lambda_s = \frac{\lambda_u}{2\gamma_r^2} (1 + K^2/2).$$

— 3 Possible alternatives:

- | |
|---|
| • Fixed beam energy, variable gap. |
| • Fixed beam energy, two different lines (variable gap for each, different undulator period) |
| • Tunable beam energy, fixed gap and fixed undulator period. |

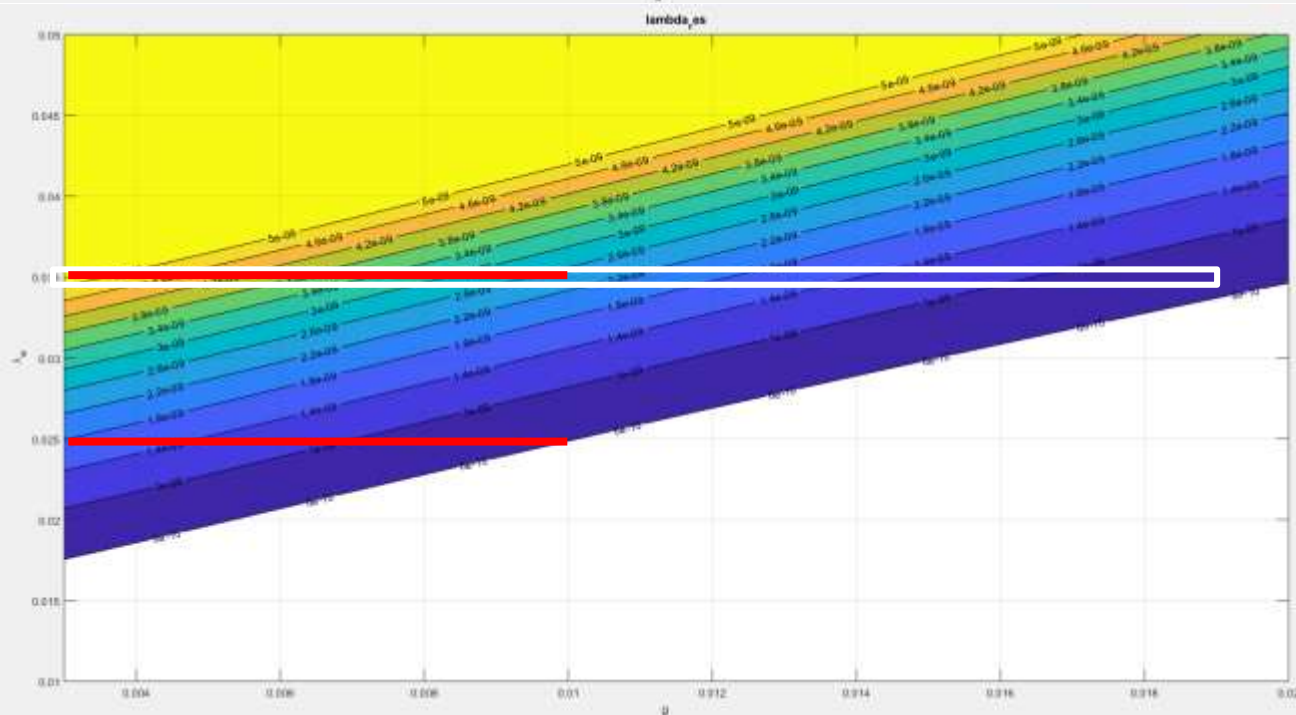
Delta undulator (wavelength)

Planar



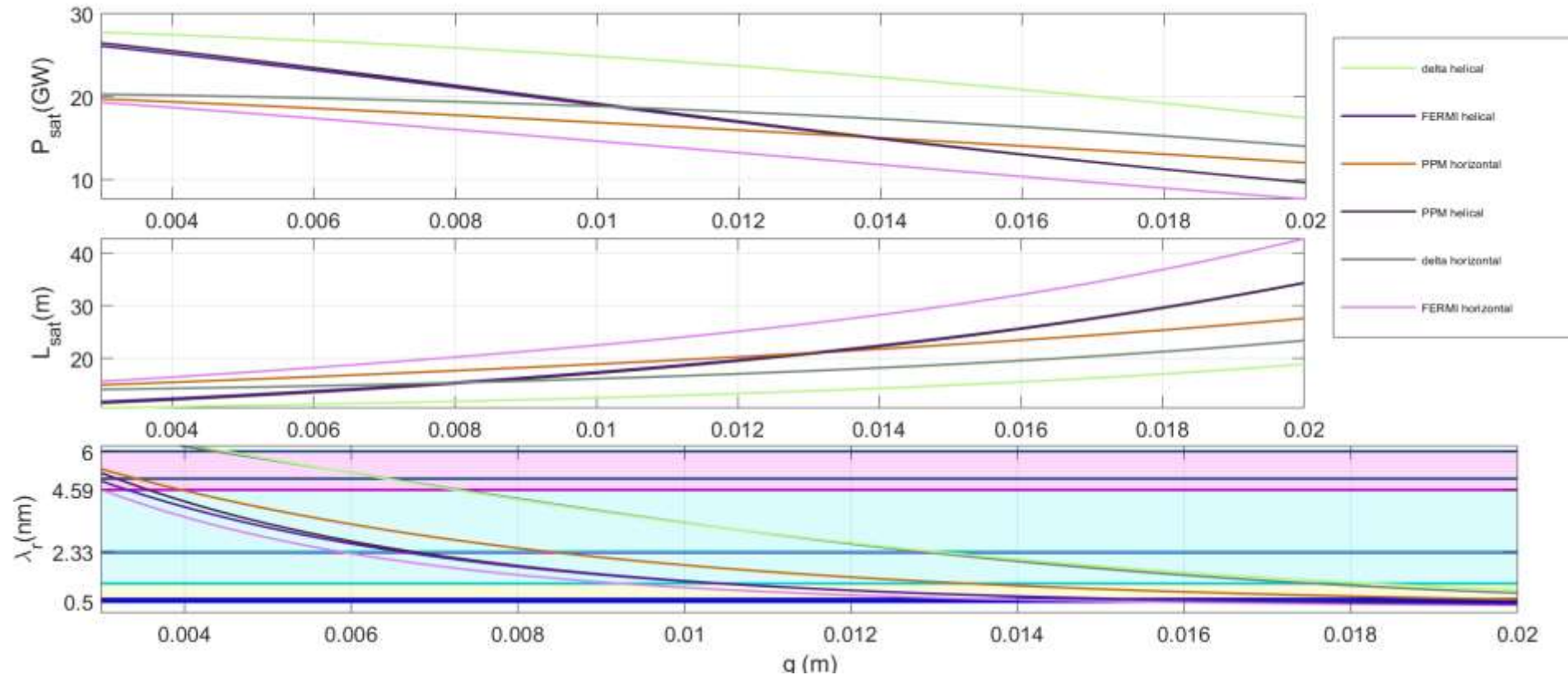
Option in white:
One line
Option in red:
Two lines

Helical



**Fixed gap and fixed beam energy
alternative (polarisation and
multicolour)**

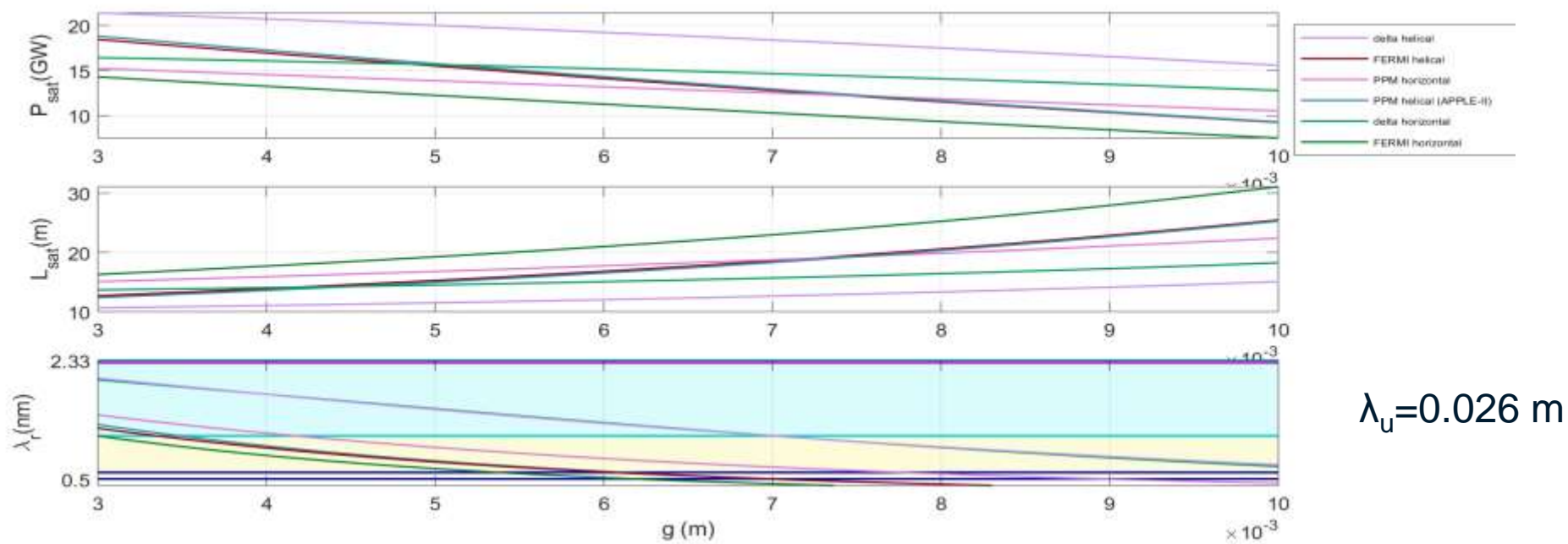
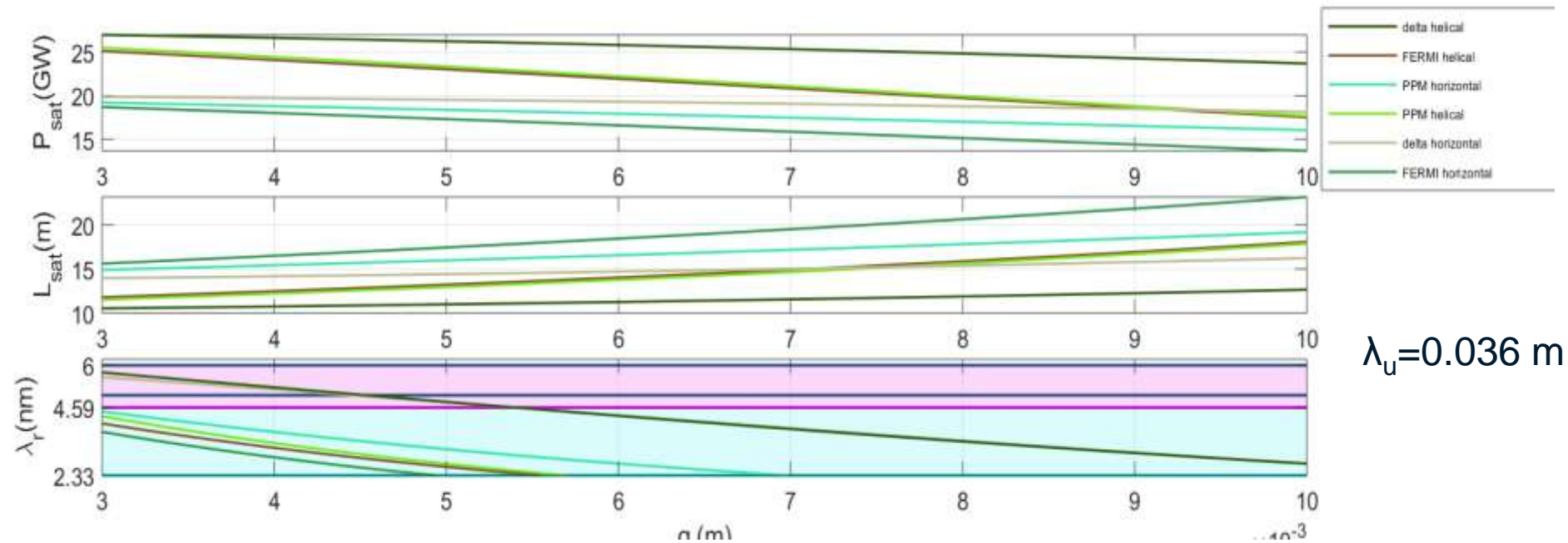
Scan over undulator periods for fixed $\lambda u=0.038$ m



Summary of Ming-Xie results (Soft X-Rays)

Undulator type	λ_{min}				λ_{max}			
	Gap (m)	λ (nm)	L_{sat} (m)	P_{sat} (GW)	Gap(m)	λ (nm)	L_{sat} (m)	P_{sat} (GW)
Delta helical	0.01915	0.6632	14.65	13.04	0.003	5.08	6.789	17.96
Delta horizontal	0.01915	0.5986	19.37	10.05	0.003	4.954	9.29	12.16
PPM horizontal	0.01906	0.6	20.85	9.79	0.003	5.074	9.93	11.93
PPM helical	0.01473	0.602	17.7	10.84	0.003	5	7.306	17.73
Fermi vertical	0.01448	0.6	22.08	9.45	0.003	5.047	10.31	11.84
Fermi helical	0.01448	0.7294	15.91	13.1	0.003	5.383	7.508	17.43

Multicolour with two lines

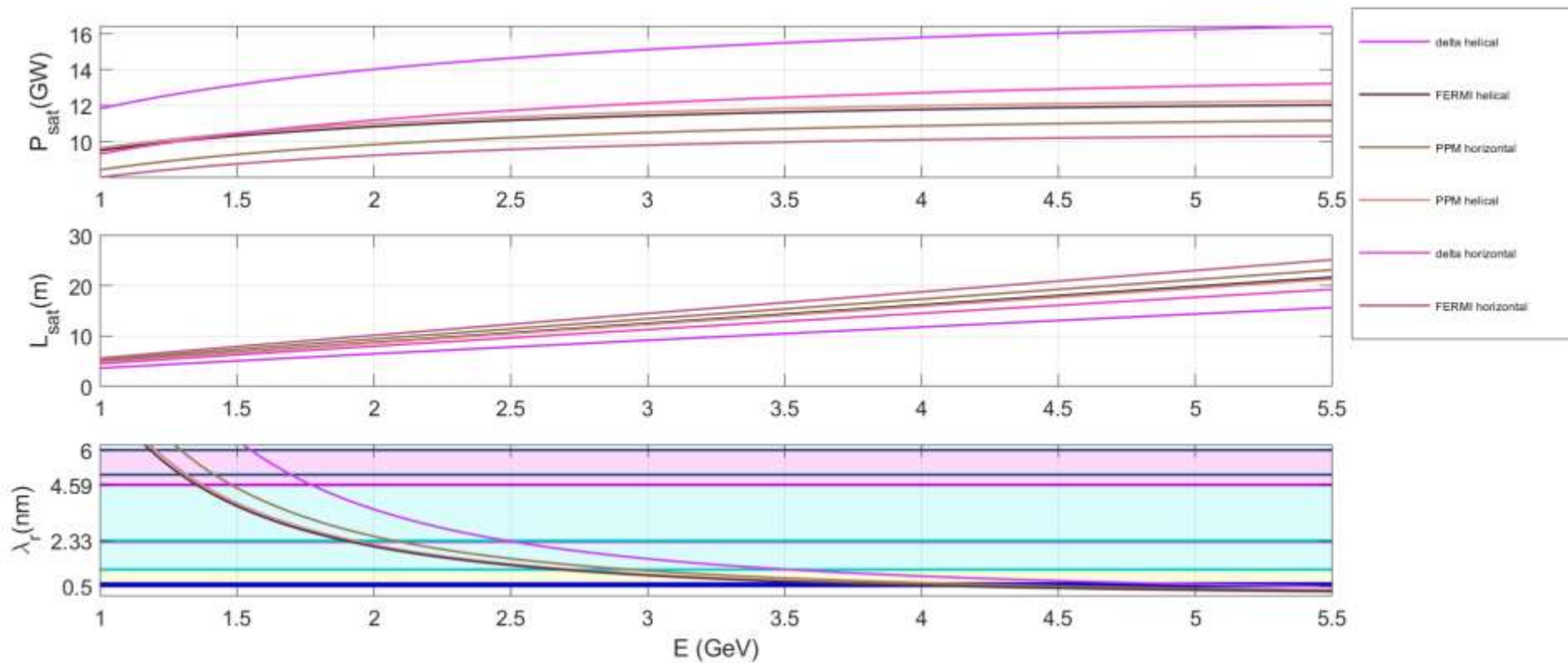


Implications

- Saturation length for delta helical between 10.5 m and 12.6 m (for the first region, $\lambda_u = 0.036$ m) and 10.6 m and 15 m (for the second spectral region, $\lambda_u = 0.026$ m). Shortest saturation length amongst the considered undulator technologies.
- Saturation Power for delta helical between 23.7 GW and 27 GW (for the first region, $\lambda_u = 0.036$ m) and 15.6 GW and 21.3 GW (for the second spectral region, $\lambda_u = 0.026$ m). Largest saturation power amongst the considered undulator technologies.

Energy tuning (fixed gap)

Comparison of saturation power, saturation length and wavelength (fixed gap)



$$\lambda_u = 0.02 \text{ m}$$

Conclusions and Outlook

List of possibilities

Option	# undulator lines	Tuning method	Undulator period [cm]	Maximum gap [mm]	Electron beam energy
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- **Option 1 – problem with large gap range?**
- **Option 2 – suitable if ok with 2 undulator lines**
- **Option 3 excluded due to energy tuning?**
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Conclusions

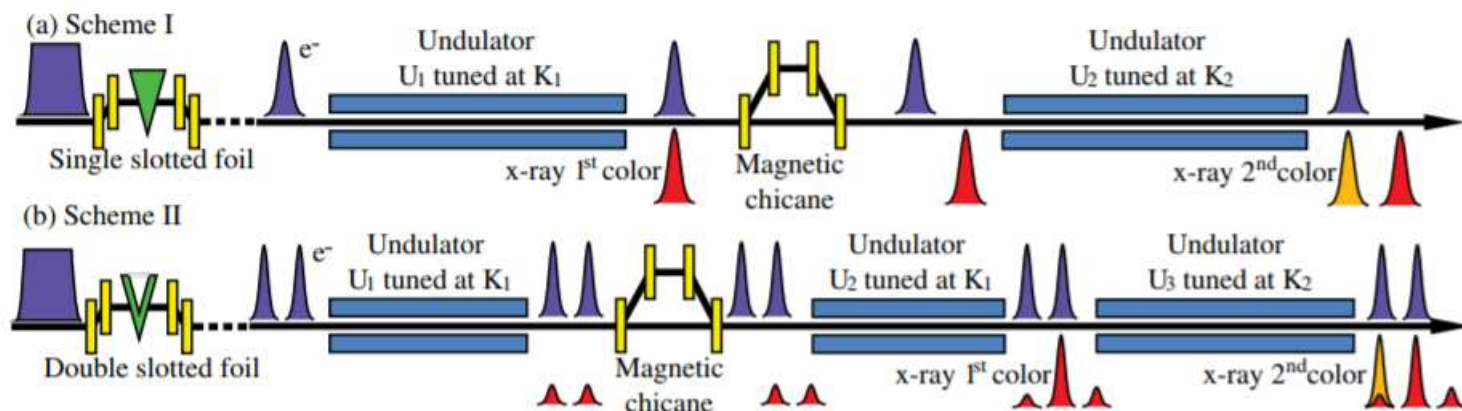
- In terms of multicolour, the feasibility of cover the multicolour regime as specified by users depends strongly on the fixed undulator period.
- A single undulator line will cover the whole spectral range if the chosen undulators are tunable to have gaps larger than 17 mm regardless of their technology (shorter wavelengths).
- A design of two undulator lines with different undulator periods allows the spectral range to be covered.
- Helical undulators (delta) show the largest saturation power (tens of MW) and the shortest saturation length (around 15 m).
- **Critical issue: Considering the two section undulators multicolour scheme, the total undulator length should exceed the sum of the saturation lengths of both colours plus the length of the chicane.**

Additional slides

Experimental verification of multicolour scheme for hard X-Rays at
SACLA (2013)

Multicolour scheme for hard X-Rays

Multicolour scheme used¹



- Fixed undulator period, gap adjustable so that the two undulator sections are set up to a different resonant wavelength.
- Combined with slotted foil scheme to demonstrate pulse duration and spectral separation: Scheme I to control electron bunch duration and Scheme II to produce multi bunches with variable delay
- Tuneable time separation due to introduction to chicane between the sections.
- Beam energy of 5.8 GeV, undulator period of 3 cm, bunch duration 18 fs FWHM, peak current of 1.6 kA.
- Maximum delay by chicane: 25 fs. Difference in average photon energy of 20 eV.

Lutman, A. A. et al. Experimental demonstration of femtosecond two-colour x-ray free-electron laser. Phys. Rev. Lett. 110, 134801 (2013).

Multicolour scheme used¹

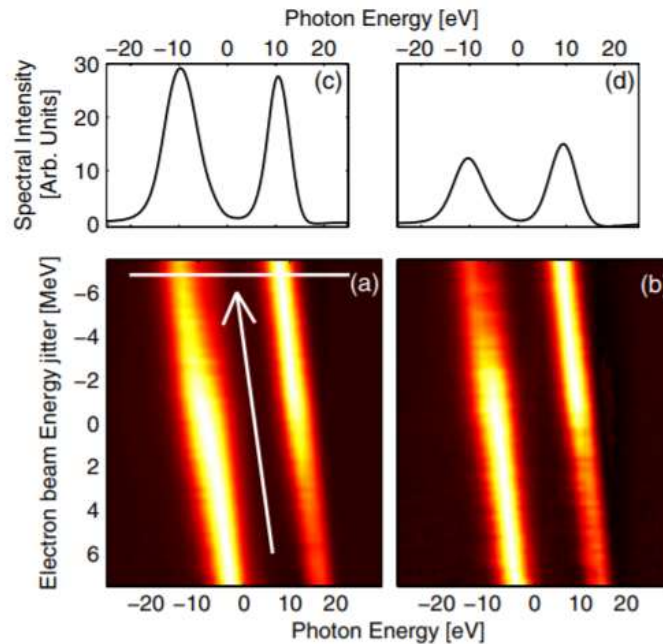


FIG. 3 (color online). Results for two-color beams with scheme I. (a),(b) Average spectral intensity as a function of the electron beam energy and photon energy. For each electron beam energy, the maximum intensity has been normalized to 1. (a) 0 fs delay. (b) 25 fs delay. (c,d) Average realigned spectra as a function of the photon energy offset from 1.5 keV. (c) 0 fs delay. (d) 25 fs delay.

Lutman, A. A. et al. Experimental demonstration of femtosecond two-colour x-ray free-electron laser. Phys. Rev. Lett. 110, 134801 (2013).

Multicolour scheme considered (hard x-rays)¹

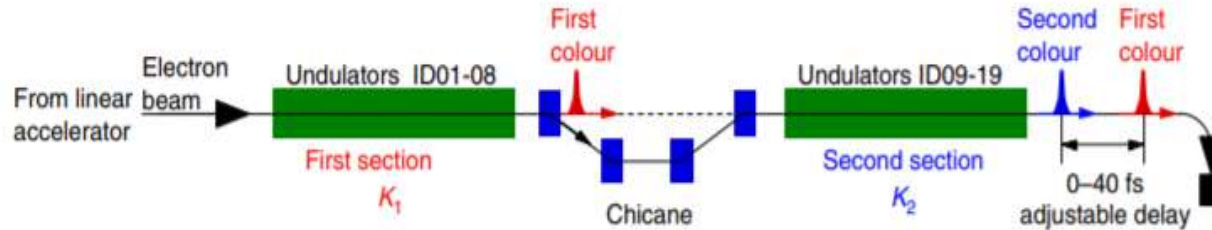


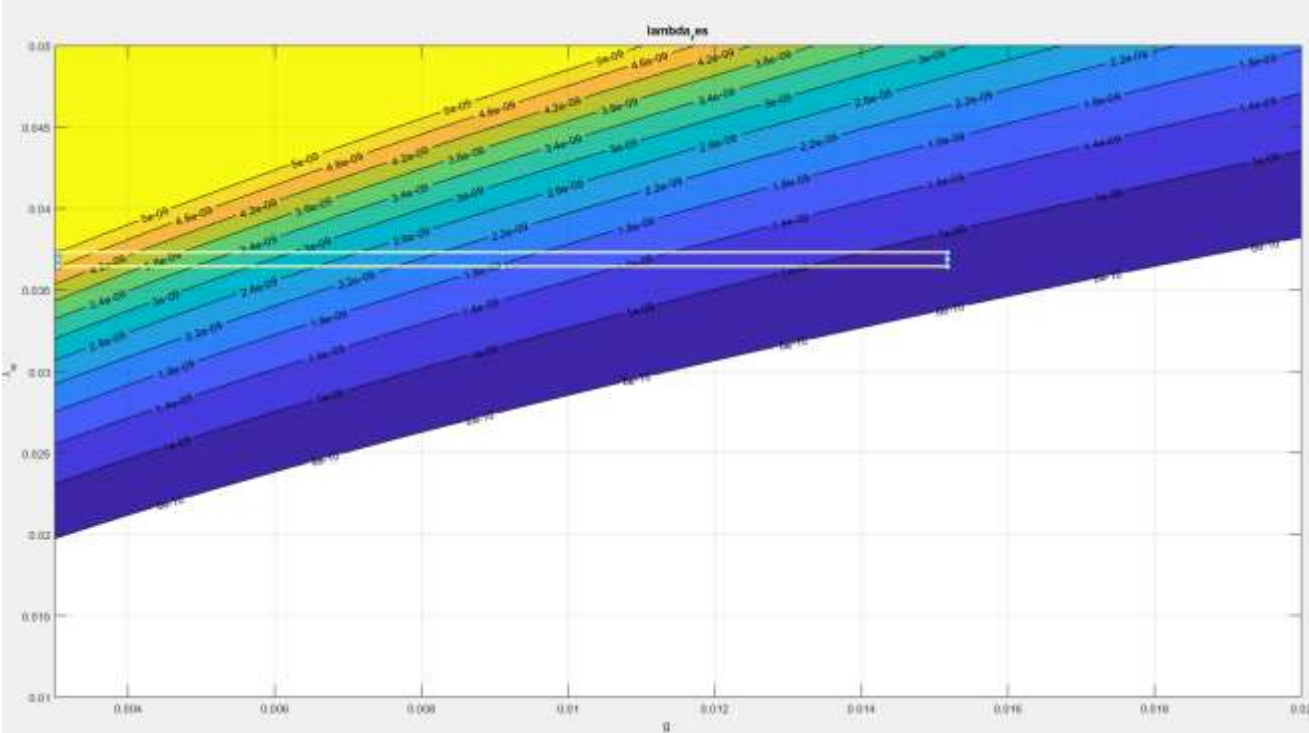
Figure 1 | Schematic layout of the SACLA undulator beamline.

- Fixed undulator period, gap adjustable so that the two undulator sections are set up to a different resonant wavelength.
- Tunable time separation due to introduction to chicane between the sections.
- Beam energy of 7.8 GeV, undulator period of 1.8 cm.
- Maximum time delay of 40 fs.
- Photon energies of 9.75 keV and 11 keV.

Hara, T. *et al.* Two-colour hard X-ray free-electron laser with wide tunability. *Nat. Commun.* **4**, 2919 (2013).

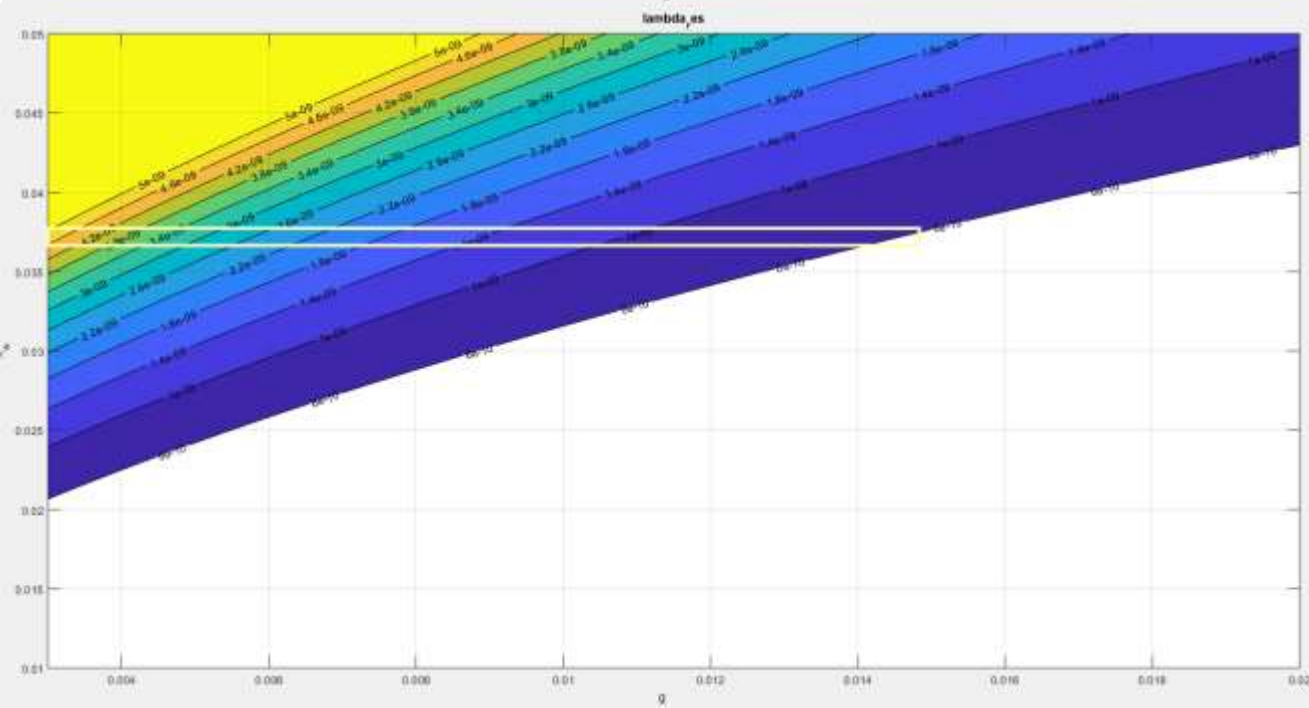
Contour plots for different technologies

EXTRA RESULTS FIXED GAP, FIXED ENERGY



PPM(wavelength)

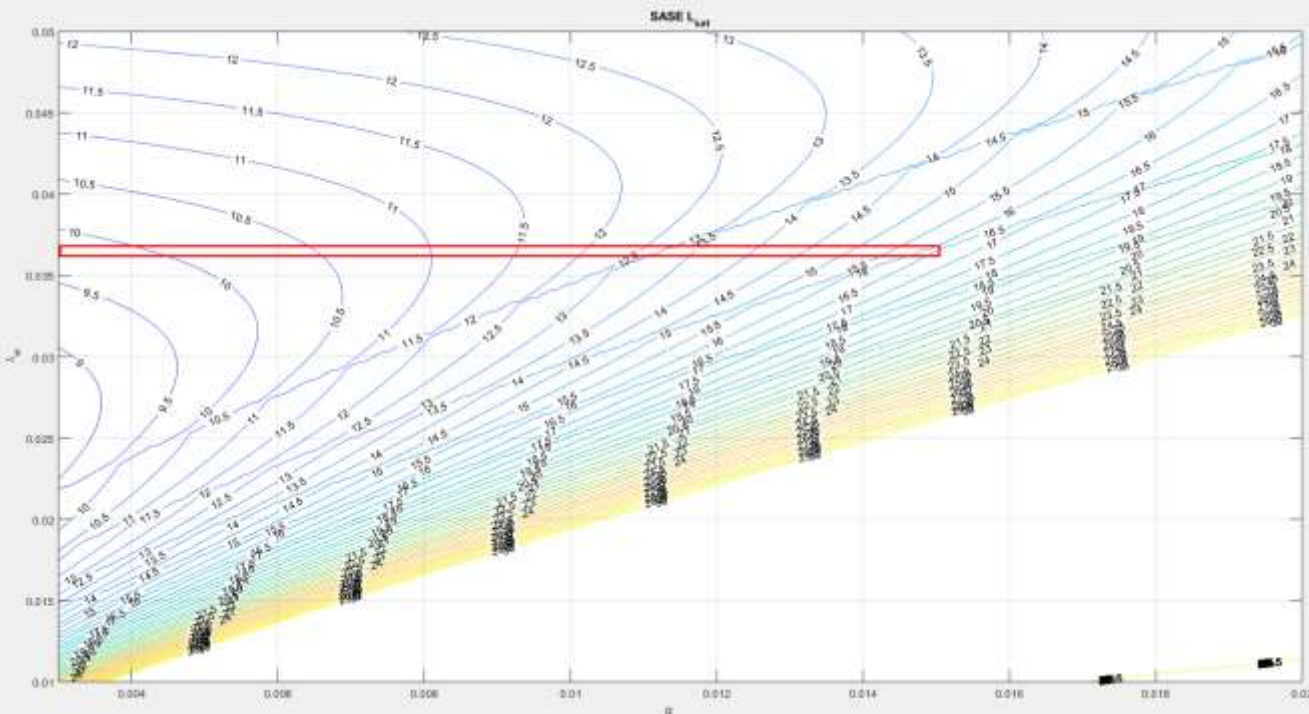
Planar



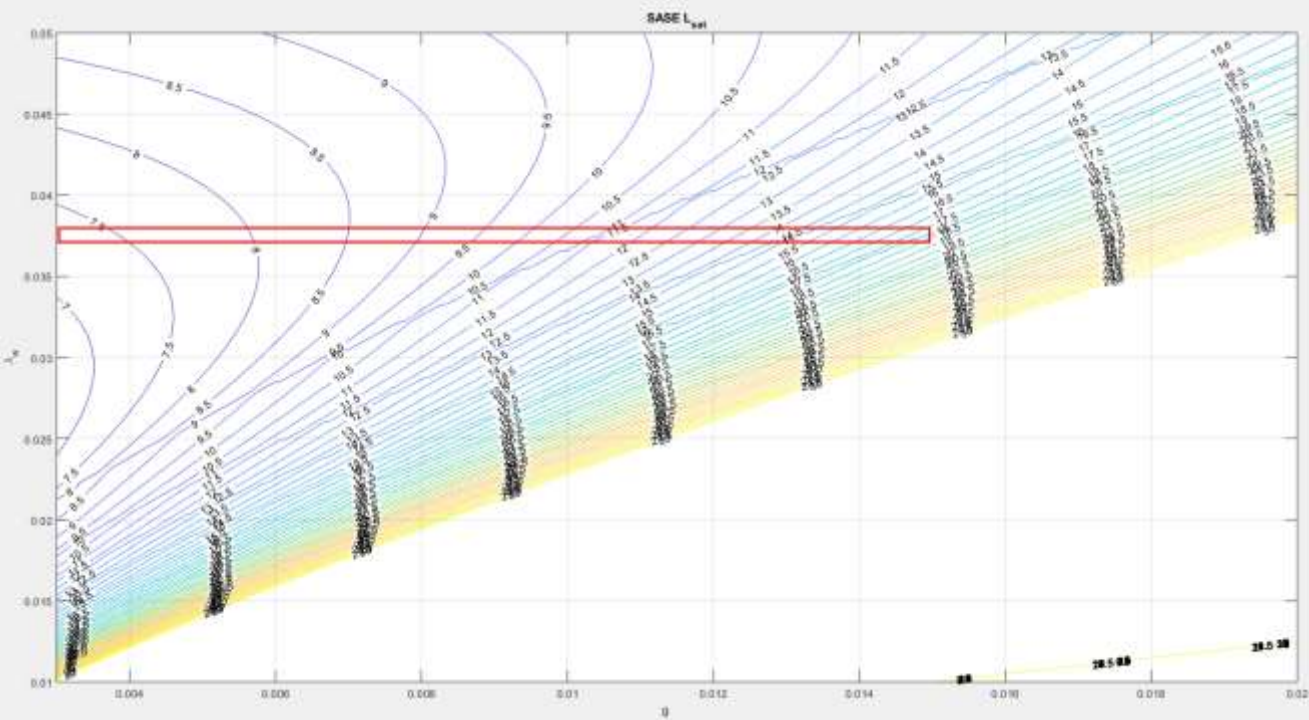
Helical

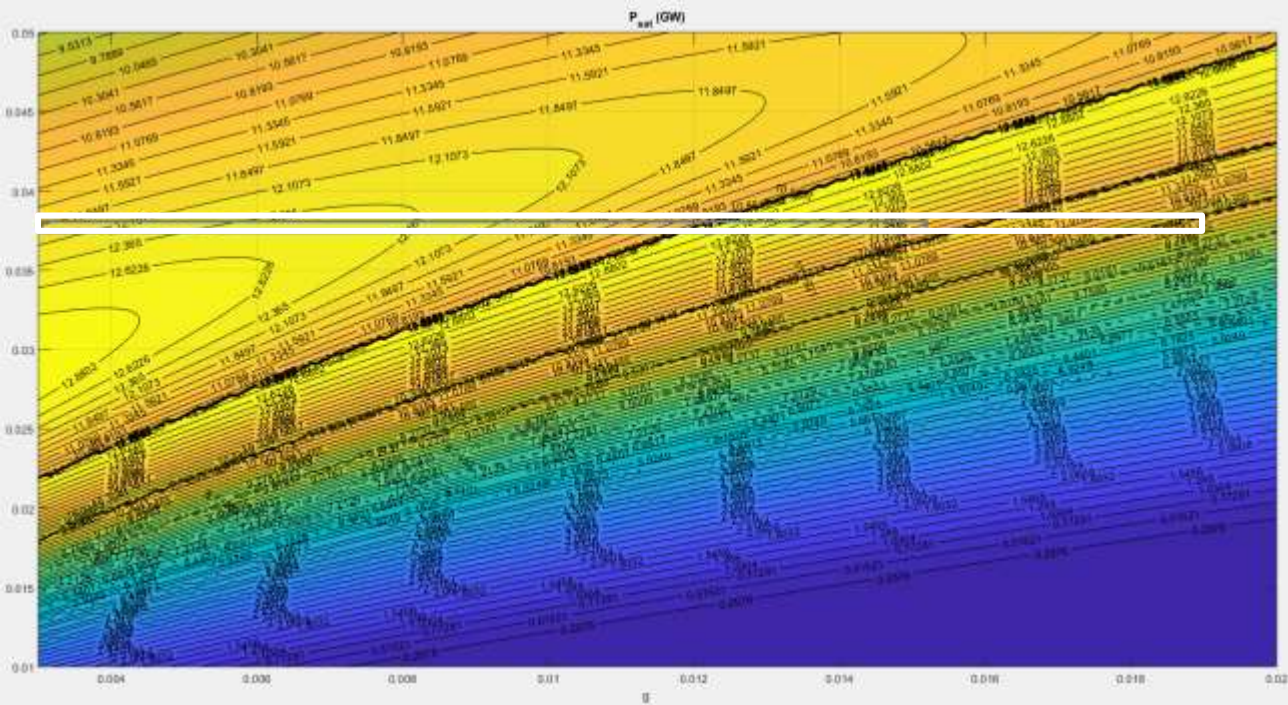
PPM undulator
saturation length)

Planar



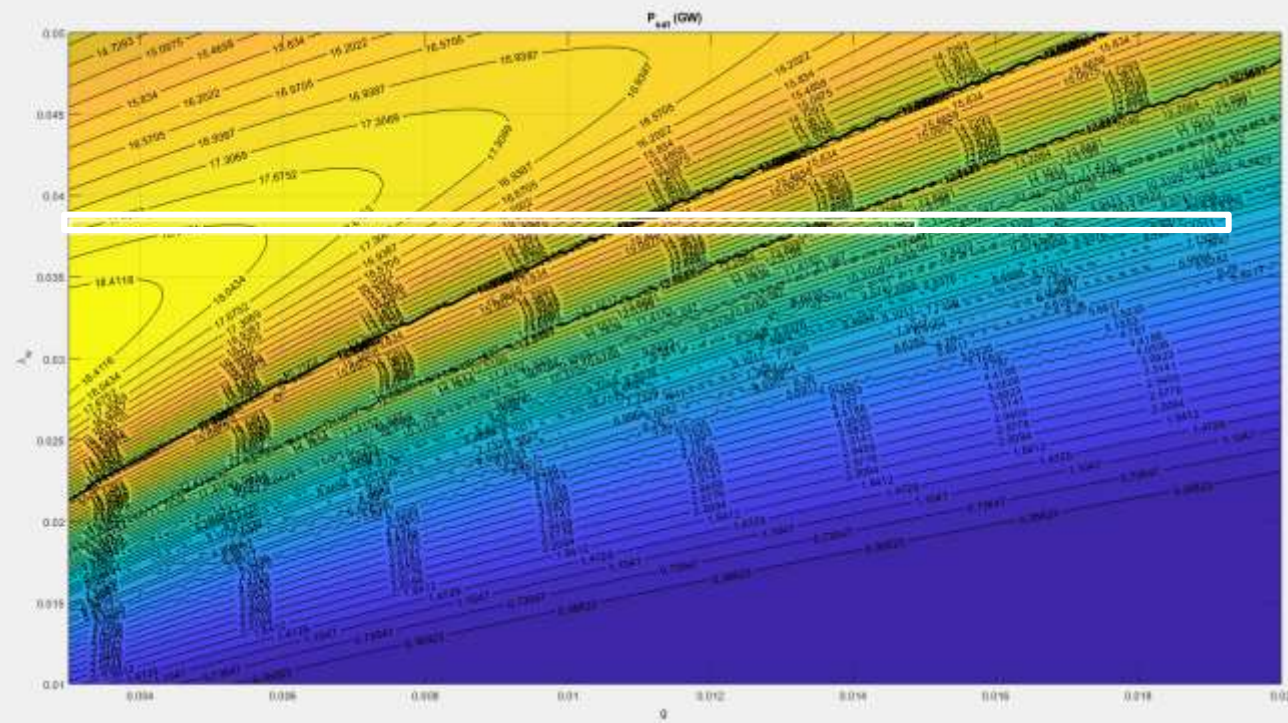
Helical





PPM(saturation
power)

Planar



Helical



Undulator type	λ_1				λ_2			
	λ_{min} (m)	Gap (m)	L_{sat} (m)	P_{sat} (GW)	λ_{max} (m)	Gap (m)	L_{sat} (m)	P_{sat} (GW)
Delta helical	5.016	0.01711	14.04	27.17	6.009	0.0153	13.47	27.85
Delta horizontal	4.992	0.01694	18.33	20.23	5.956	0.01533	17.72	20.55
PPM horizontal	5	0.0197	15.87	11.64	6		14.73	19.65
PPM helical	5.006	0.008865	14.36	26.91	6.009	0.0078	13.76	27.62
Fermi helical	4.997	0.008695	14.48	27.03	5.962	0.0076	13.9	27.72

Including the additional option of tunable beam energy and variable gap

WORK ON PPM UNDULATORS BY DAVE DUNNING

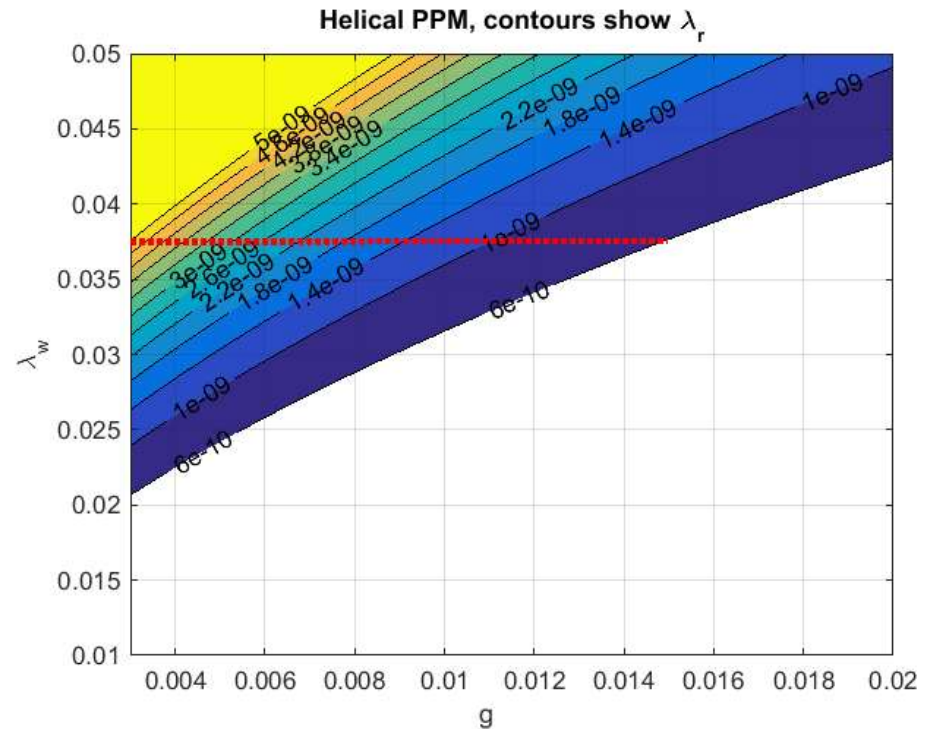
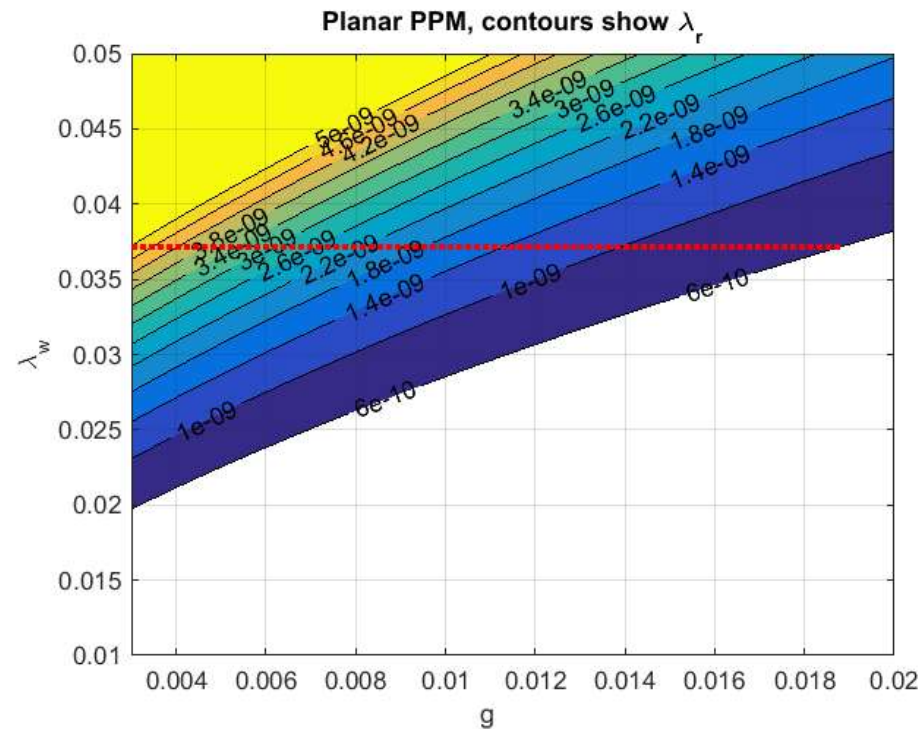
Assumptions

- Minimum gap = 3 mm
- Nominal energy = 4 GeV
- PPM undulator (just as an example)
- Polarisation – varied by changing all undulators together (i.e. not using an afterburner scheme)

(It is probably worth revisiting these on the basis of the following results)

Option 1

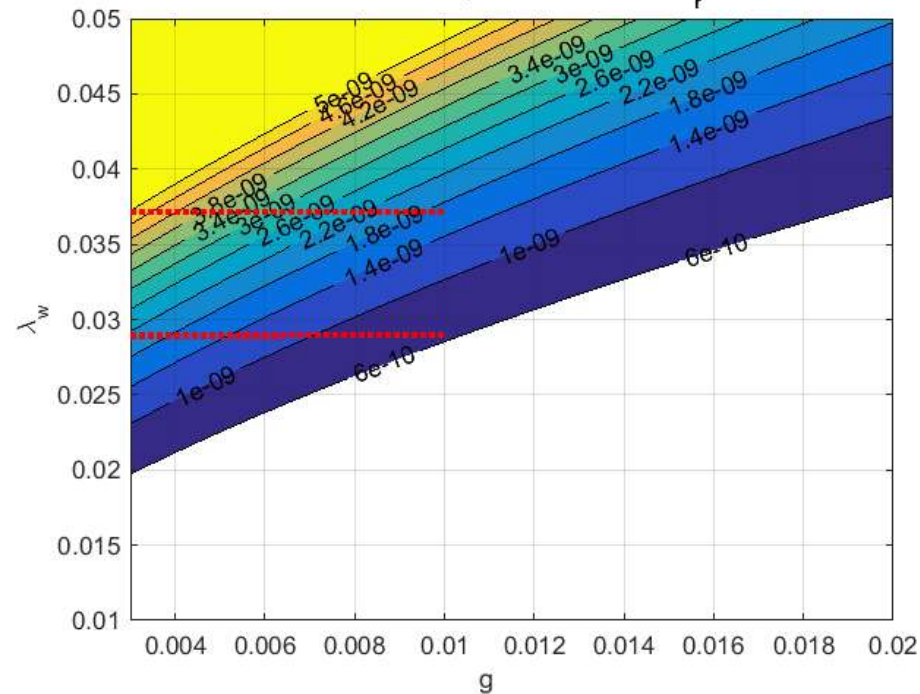
- Fixed energy (4 GeV), variable gap
- One undulator line
 - $\lambda_r \sim 3.7$ cm, gap range ~ 3 -19mm (large maximum gap)



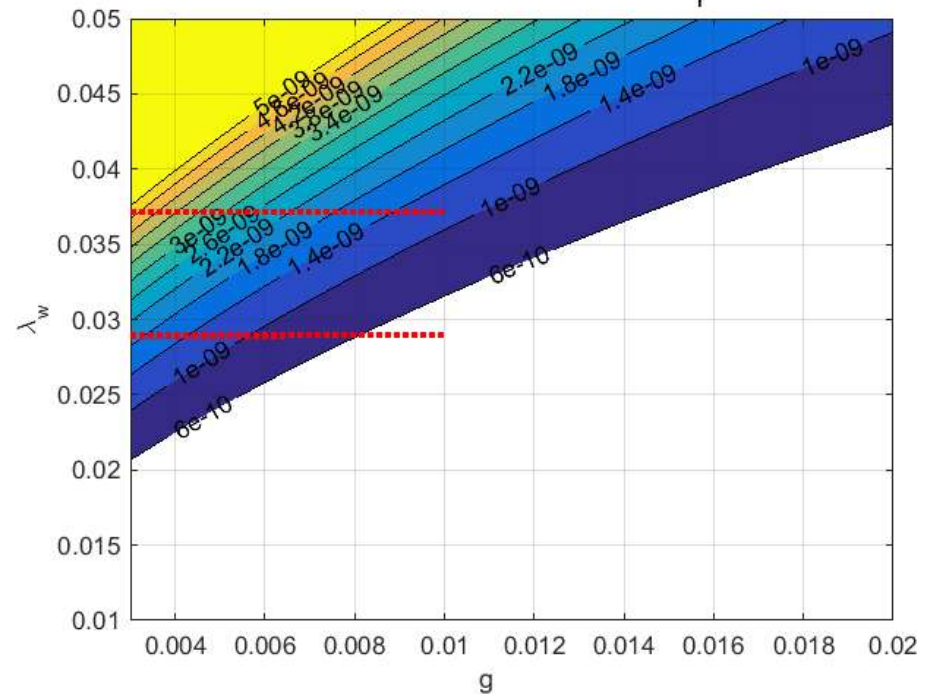
Option 2

- Fixed energy (4 GeV), variable gap
- Two undulator lines
 - FEL 1: $\lambda_r \sim 2.9$ cm, gap range ~ 3 -10mm
 - FEL 2: $\lambda_r \sim 3.7$ cm, gap range ~ 3 -10mm

Planar PPM, contours show λ_r



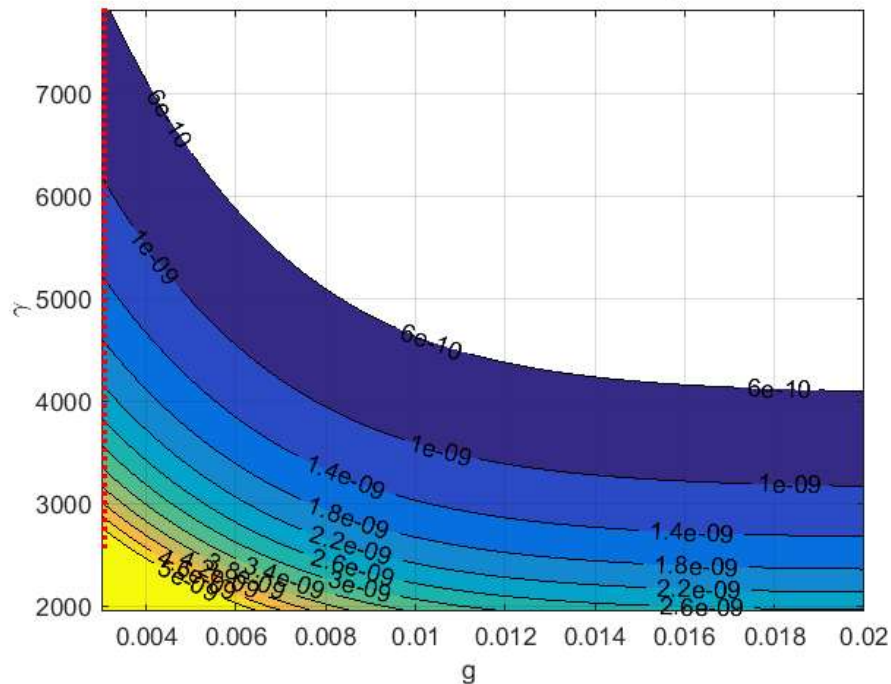
Helical PPM, contours show λ_r



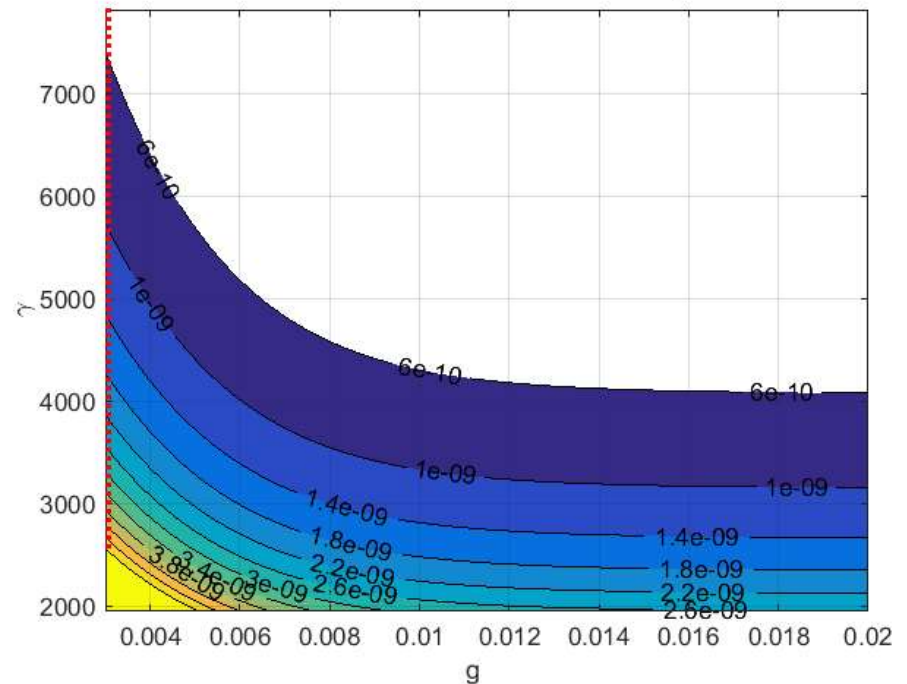
Option 3

- Fixed gap (3 mm), variable electron energy (not recommended!)
 - One undulator line
- $\lambda_r \sim 2.0$ cm, energy range ~ 1.3 -4 GeV

Planar PPM, contours show λ_r



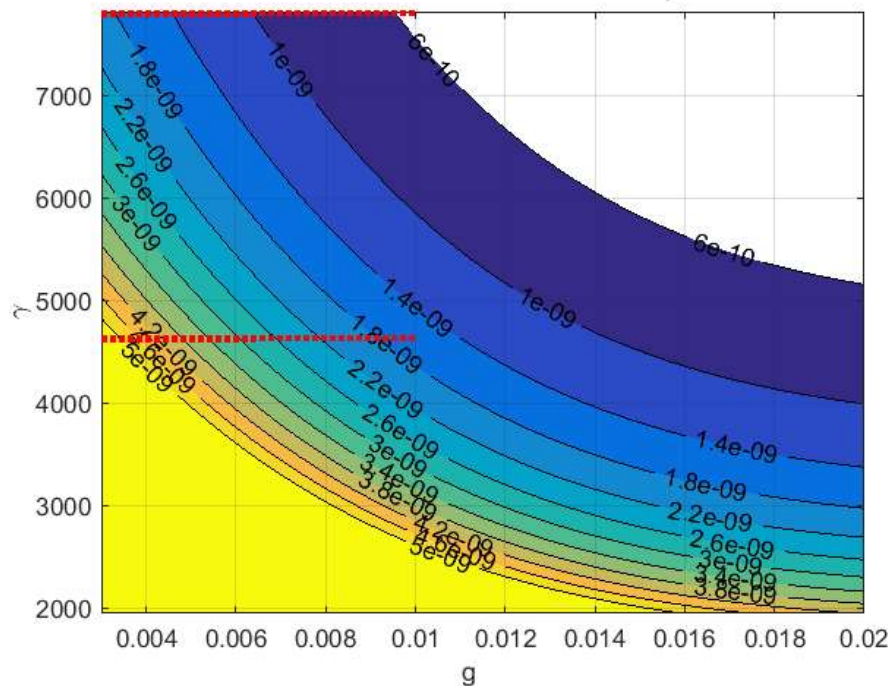
Helical PPM, contours show λ_r



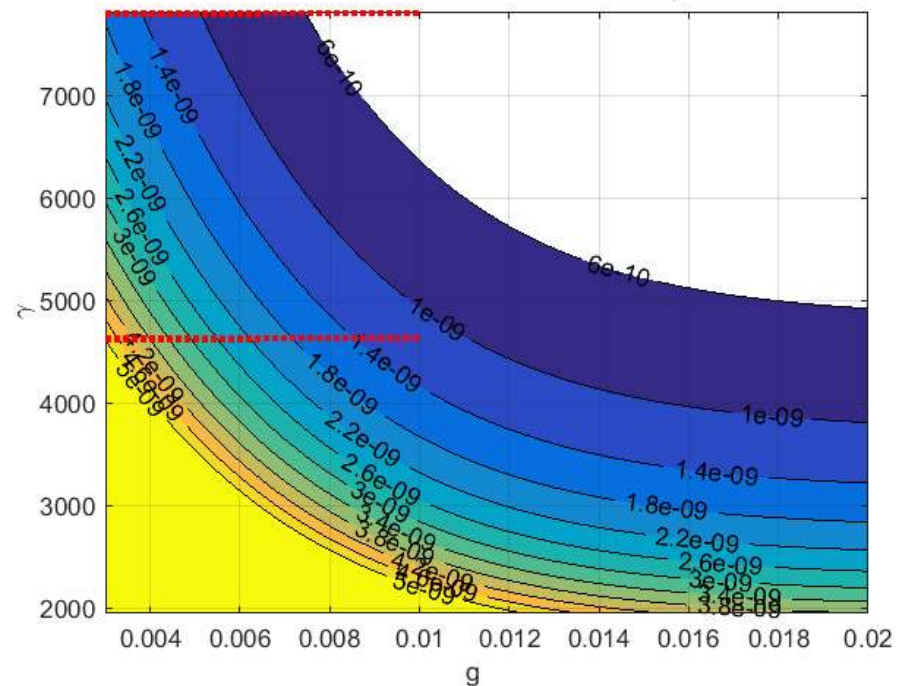
Option 4

- Variable gap and two energies
 - One undulator line
- $\lambda_r \sim 2.8$ cm, energy = 2.35/4 GeV, gap range ~ 3 -10 mm

Planar PPM, contours show λ_r



Helical PPM, contours show λ_r



Summary

Option	# undulator lines	Tuning method	Undulator period [cm]	Maximum gap [mm]	Electron beam energy
1	1	Gap tuning	3.7	19	4 GeV (fixed)
2	2	Gap tuning	2.9/3.7	10	4 GeV (fixed)
3	1	Energy tuning	2.0	3	1.3-4 GeV (variable)
4	1	Gap tuning at two different energies	2.8	10	Two fixed points: 2.35 & 4 GeV

- Option 1 – problem with large gap range?
 - Option 2 – suitable if ok with 2 undulator lines
 - Option 3 excluded due to energy tuning?
 - Option 4 – suitable if 2 energies compatible with hard x-ray etc.
- +
- Options 5,6,7, etc. - revisit assumptions!