Laser-beam and Fabry-Perot Cavity parameters For PSI cooling

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Introduction

The models used to perform the optimization will be discussed tomorrow, along with the relatd assumptions

Several parameters need to be optimized:

- Laser beam transverse sizes @ the collision point
- Laser beam pulse duration
- Laser beam Spectrum
- Crossing angle

But constraints do exist and must be acounted for:

- Fabry-Perot cavity (FPC) geometry
- Laser system parameters/flexibility
- Geometrical footprint

Could in principle optimize everything accounting for constraints with a Monte Carlo procedure (needed for a 4-mirror FPC) but it is not necessary in the case of a 2-mirror FPC.

➡ See Kevin's presentation for the motivation of a 2-mirror FPC

Assumptions in a few words

The model used is an average model that account for :

- Spectral overlap of the laser and ion beams
- Spatial overlap of the laser beam and ion beams assuming cylindrical beams
- Saturation effect of the excitation probability
- Only longitudinal dynamic effects are simulated

➡ See Simulation session for details

Use spatial ion beam parameters corresponding to LSS6-616 (Proof of principle experiment)

The ion beam longitudinal length (duration) is linearly related to energy spread

$$\sigma_{i,z} = cT_{\mathrm{c}}\sqrt{\frac{\eta\gamma_{\mathrm{i}}M_{\mathrm{i}}}{2\pi H(Z-N_{\mathrm{e}})V_{\mathrm{RF}}}}\frac{\Delta E_{\mathrm{i}}}{E_{\mathrm{i}}}.$$

Assume a fixed time bandwidth product for the longitudinal laser beam shape

→ Fourier Limited laser pulse

→ see simulation session for details

Parameters

Description	Parameter name	Value
Number of ions per bunch	n_I	$2 \cdot 10^8$
Betatron function at the IP	β^*	53 m
Normalized emittance	ϵ	$1.5 \cdot 10^{-6}$ m
Transition energy	E_t	230.76 eV
Excited state lifetime	τ	76 ps
Ion rest mass	$M_\mathrm{i}c^2$	193.687 GeV
Bunch spacing related frequency	F_rep	5 MHz
SPS revolution time	T_c	23 μs
Initial ion-beam energy spread	$\Delta E_\mathrm{i}/E_\mathrm{i}$	$3 \cdot 10^{-4}$
RF voltage magnitude	V_RF	7 MV
Ion atomic number	Z	82
Number of remaining electrons in ion	N_e	3
Harmonic number in SPS	H	4620
SPS transition energy	$\gamma_t M_\mathrm{i}c^2$	22.8 GeV
Laser-beam waist (horizontal plane)	$w_\mathrm{o,h}$	1.5mm
Laser-beam waist (vertical plane)	$w_\mathrm{o,v}$	1.5mm
Laser-beam central wavelength	λ_0	1030 nm

Cylindrical beam to ease discussions

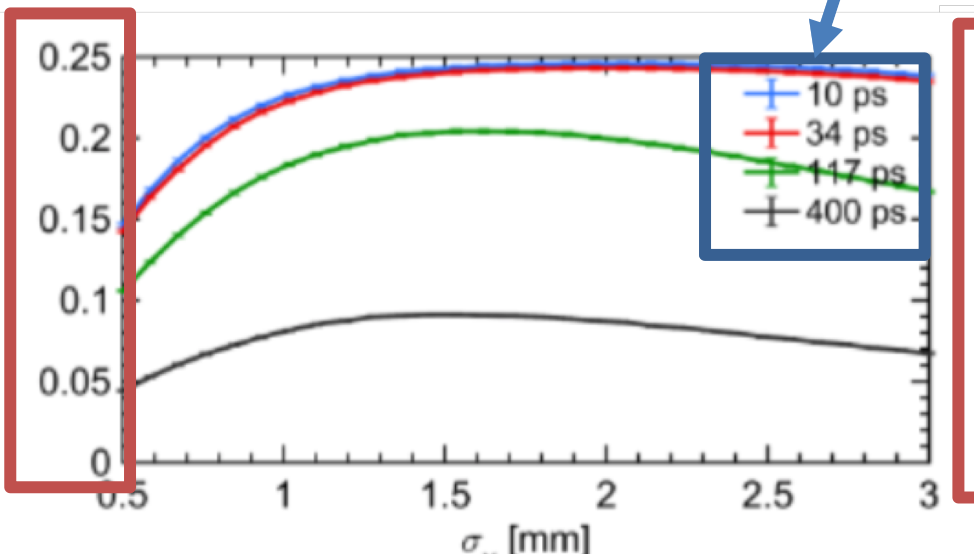
Laser beam pulse energy	5 mJ
Laser/ion beams crossing angle	2.6°

Minimal acceptable value according to geometrical contraints

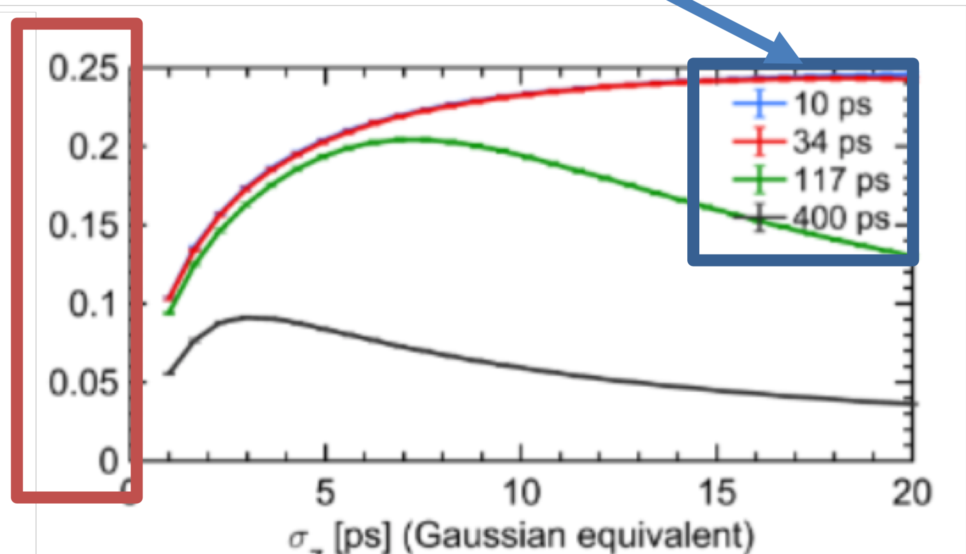
Overal optimum fraction of intercepted ions

Ion bunch duration is varied (laong with energy spread) from 400ps to 10ps

Fraction of intercepted ions maximised over all other parameters



Transverse laser-beam size



Longitudinal laser-beam size

The fraction is maxised over the other parameter

FPC design options

2-mirror FPC

- ☺ Simple geometry
- ☺ simple alignment
- ☺ Minimizes crossing angle
- ☺ Laser beam polarisation driven by polarisation of the laser.
- ☹ Circular polarisation at percent level

☺ Ellipsometry technics do exist to calibrate it at sub-percent level

4-mirror FPC

- ☹ More involved geometry: 3D
- ☹ more difficult alignment (vacuum ?)
- ☹ Crossing angle slightly increased
- 😐 Laser-beam polarization driven by FPC geometry
- 😐 High finesse cavity → resonance frequencies of 2 circular polarizations are split

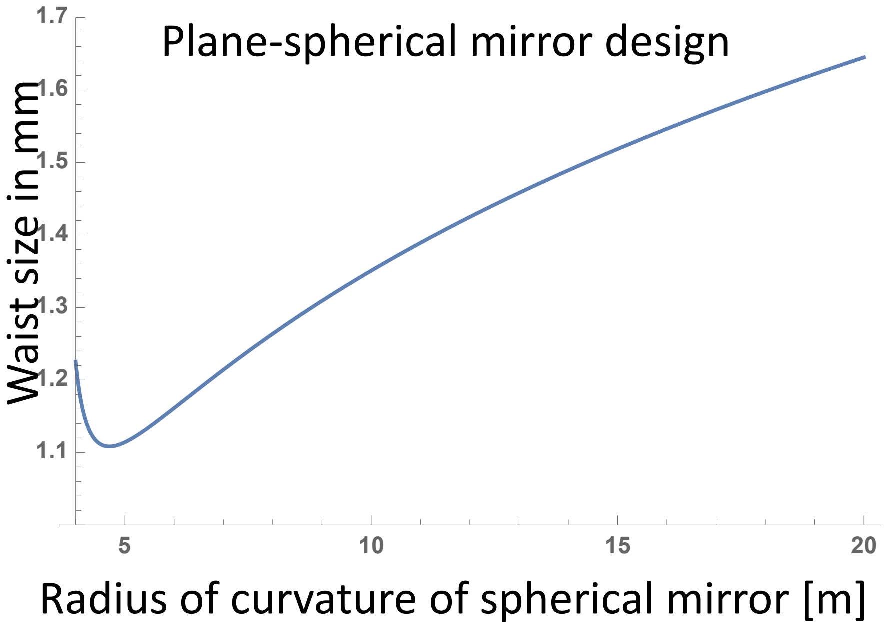
☺ Theoretically extremely small opposite circular polarization

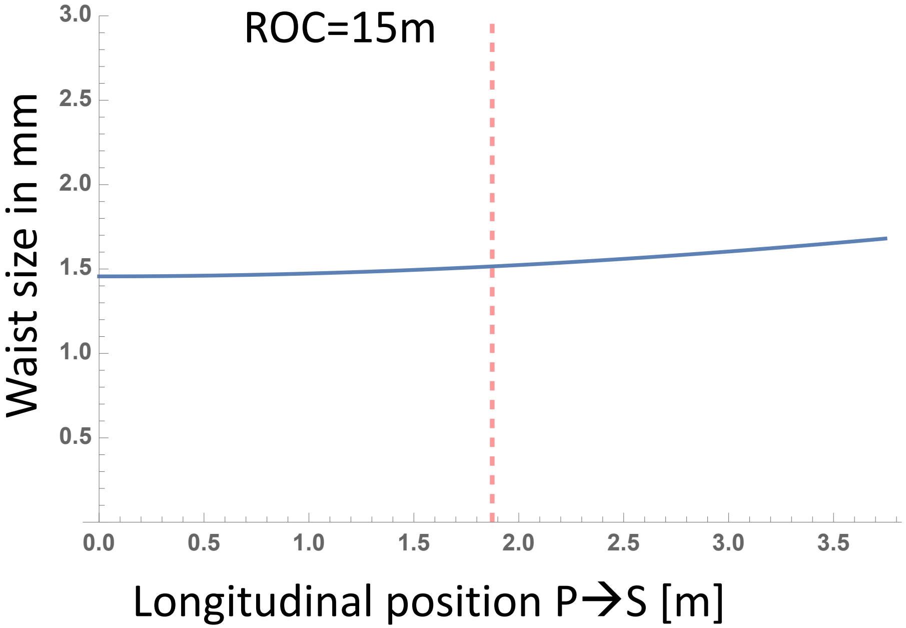
- 😐 But how to quantify ?

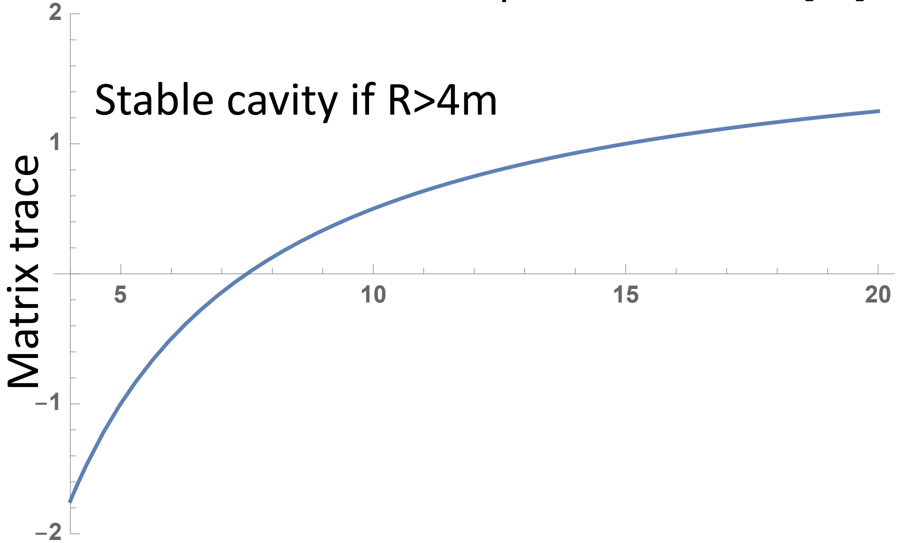
Ideal for Proof of principle experiment

Ideal for physics ? Longer term plans

FPC design 2-mirror cavity: geometry

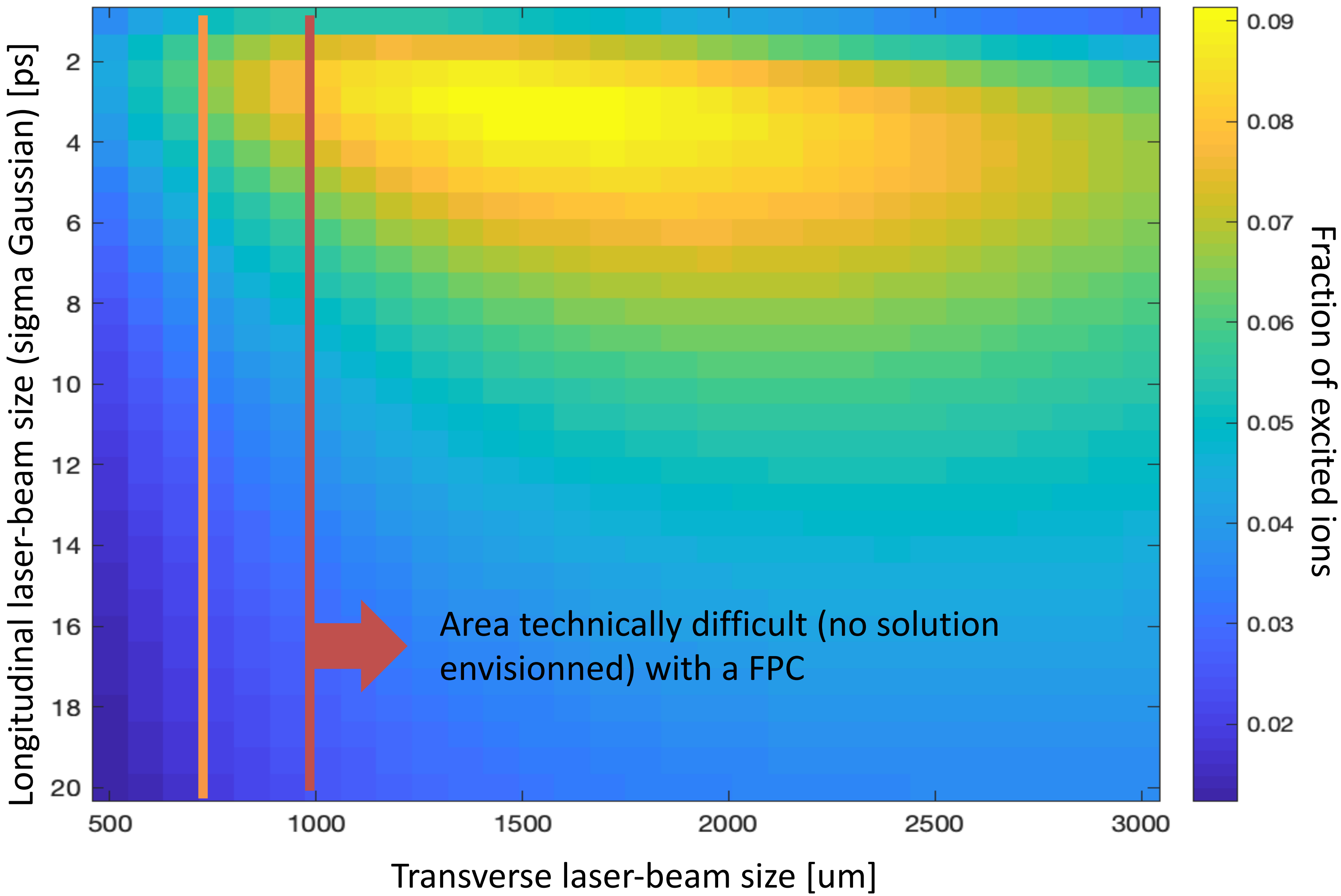




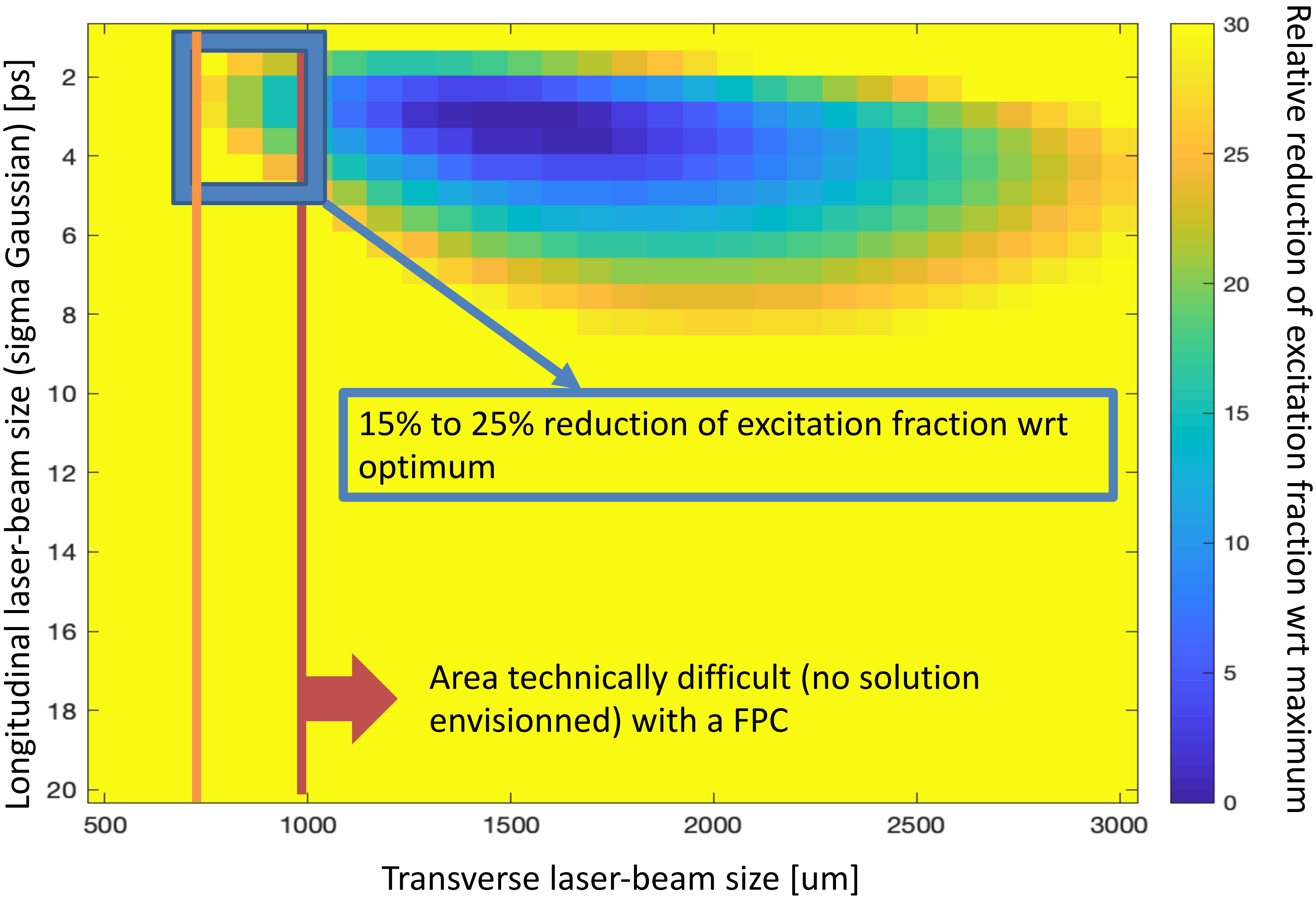


ROC=15m + flat mirror FPC gives about 15mm (round) waist at Interaction Point

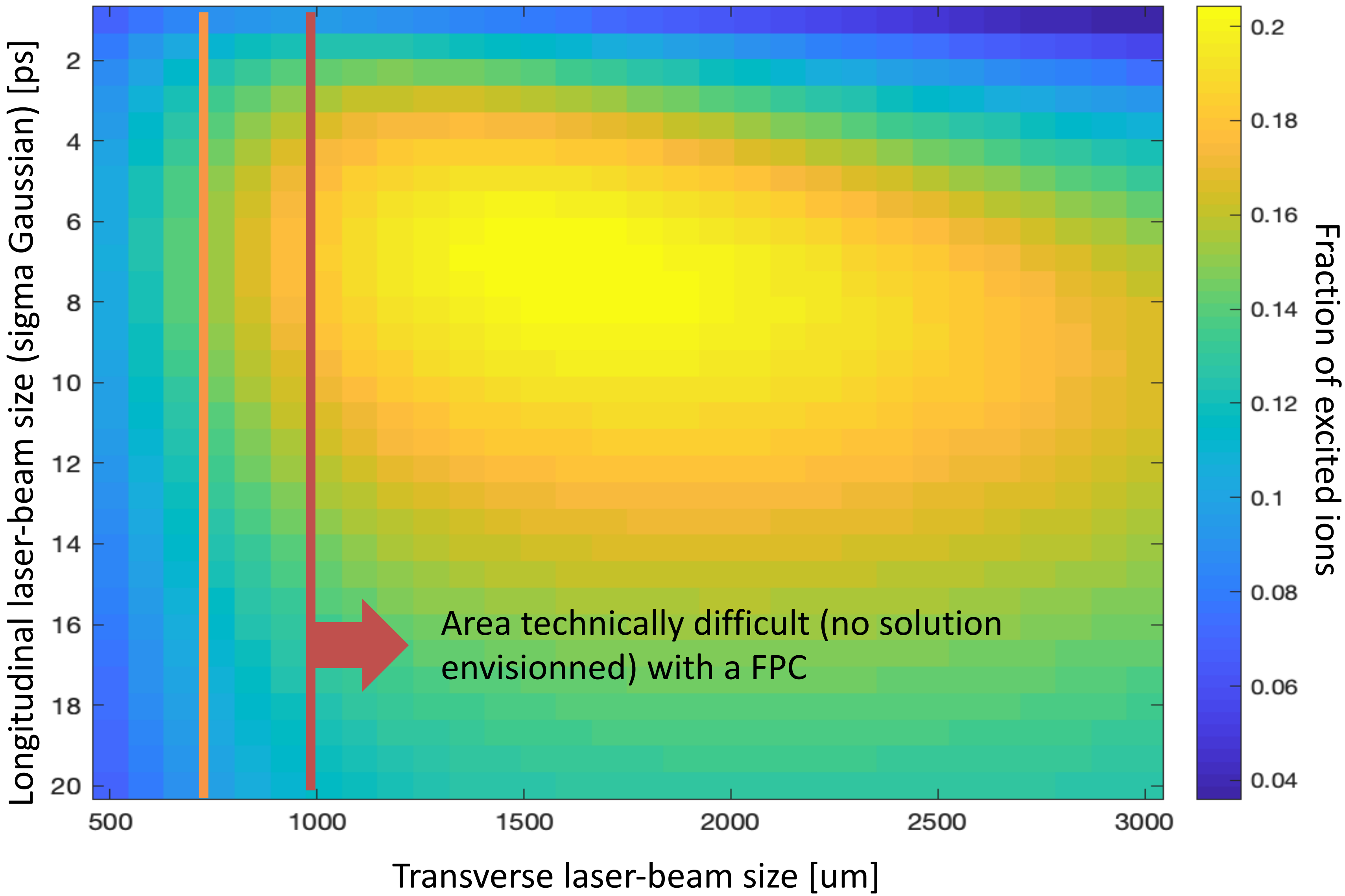
2D-distribution for 400 ps ion bunch duration



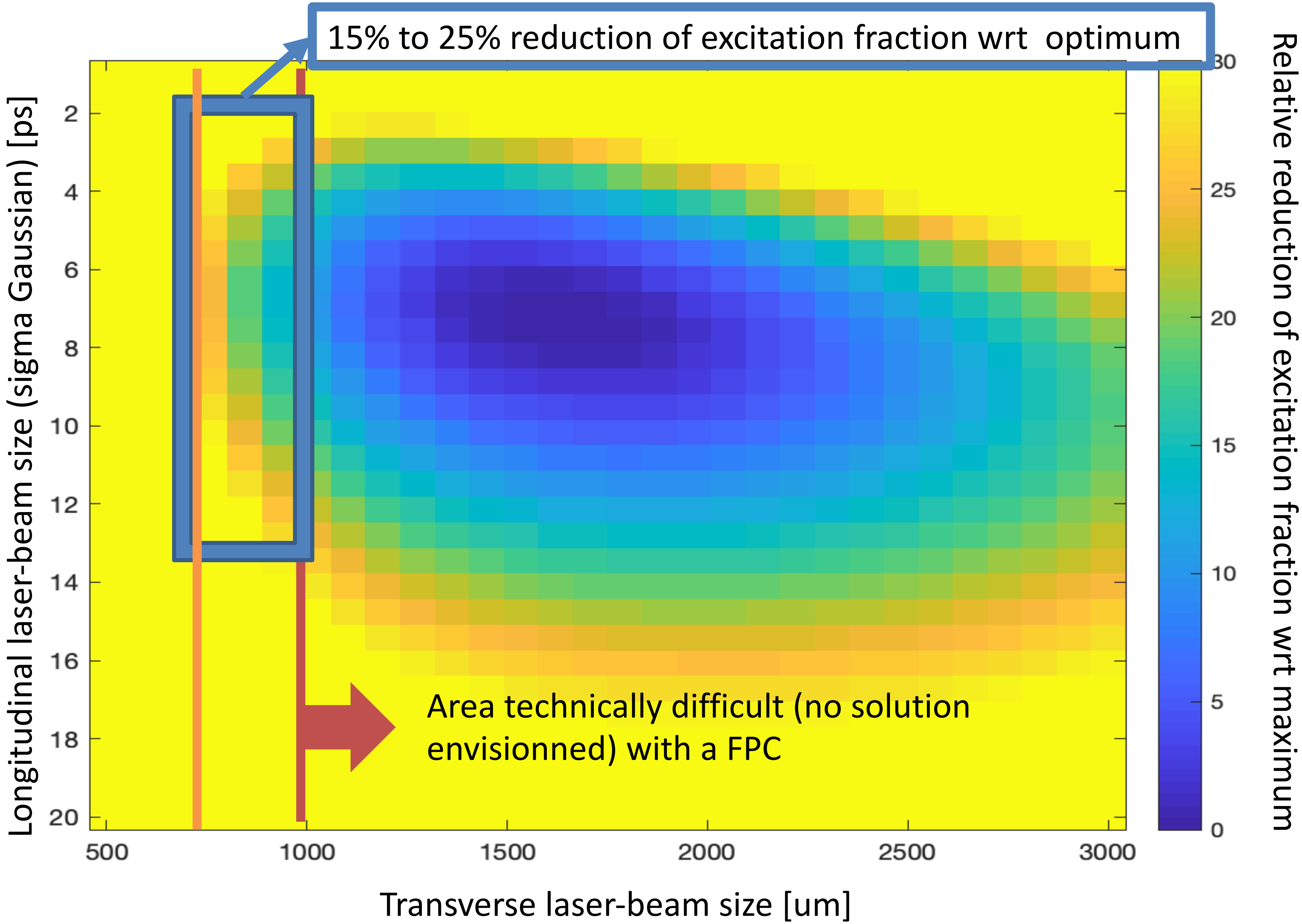
2D-distribution for 400 ps ion bunch duration



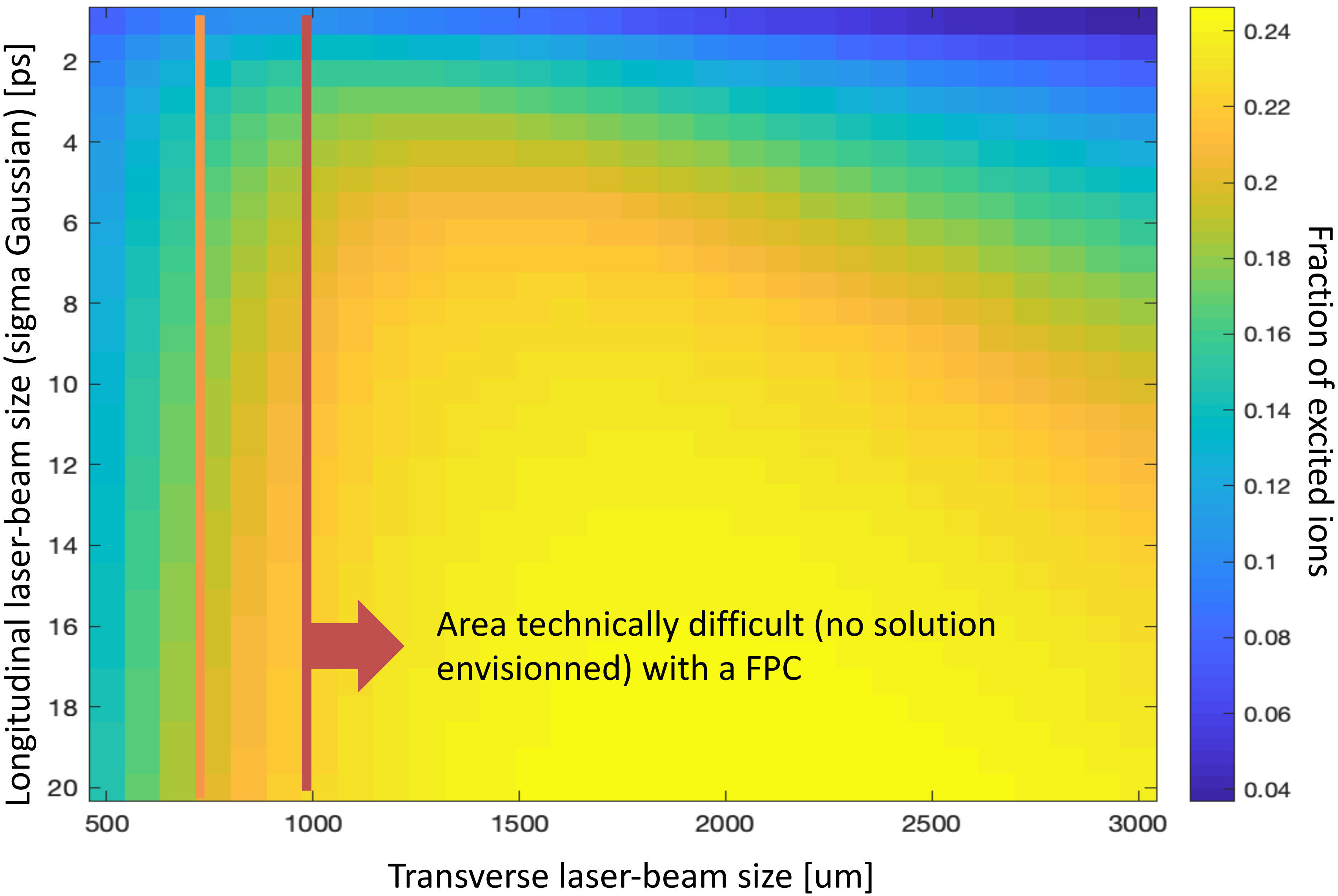
2D-distribution for 117 ps ion bunch duration



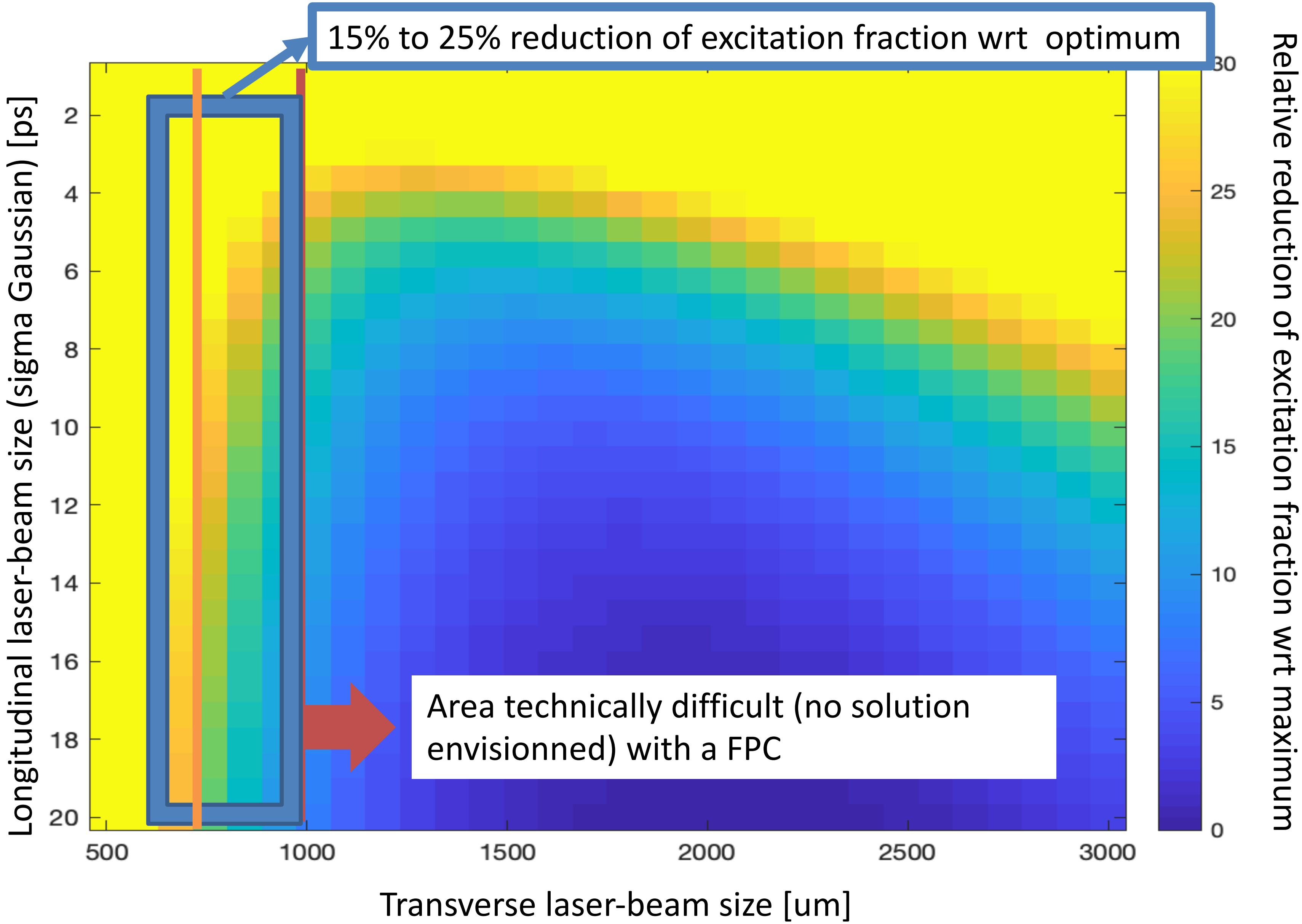
2D-distribution for 117 ps ion bunch duration



2D-distribution for 10 ps ion bunch duration

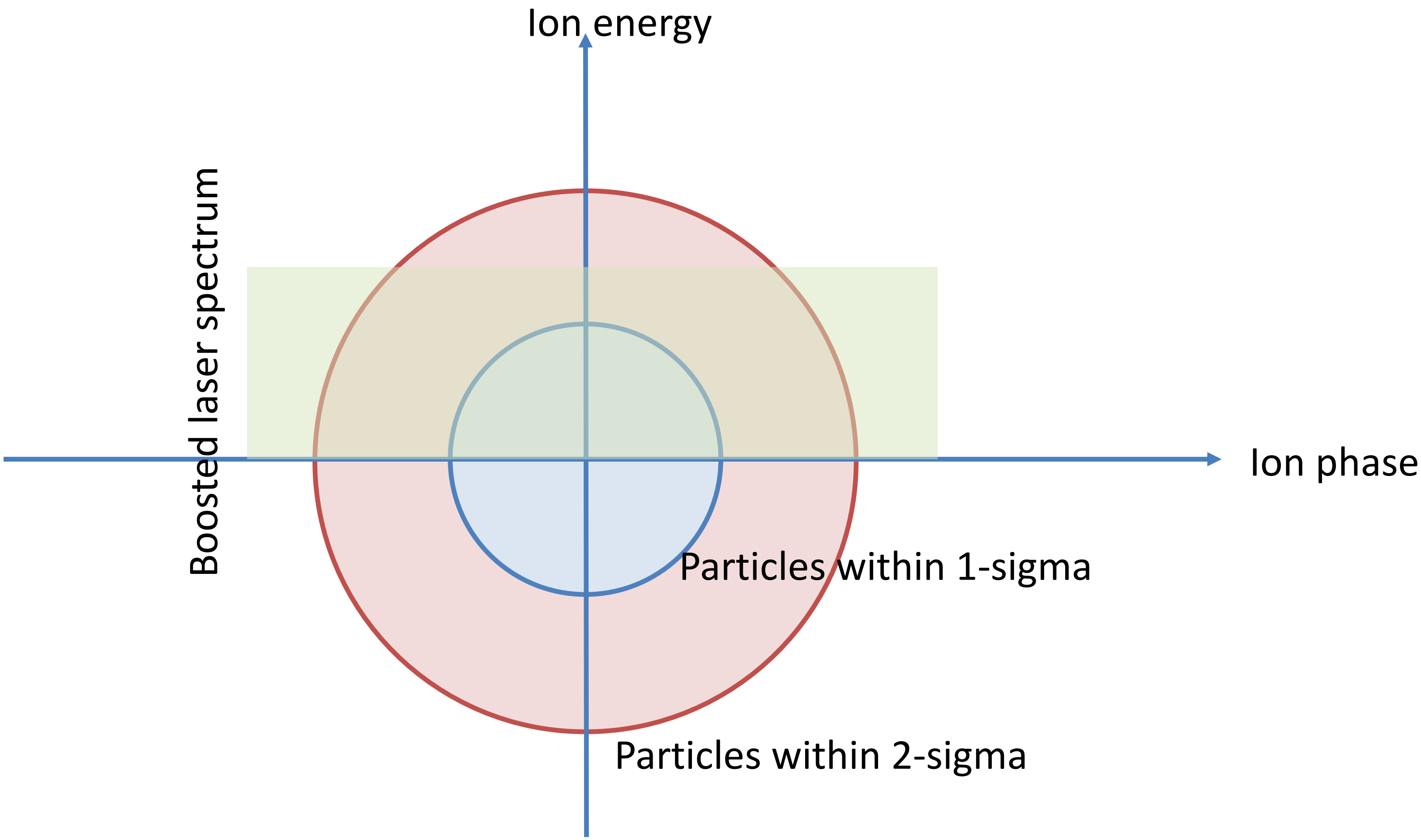


2D-distribution for 10 ps ion bunch duration



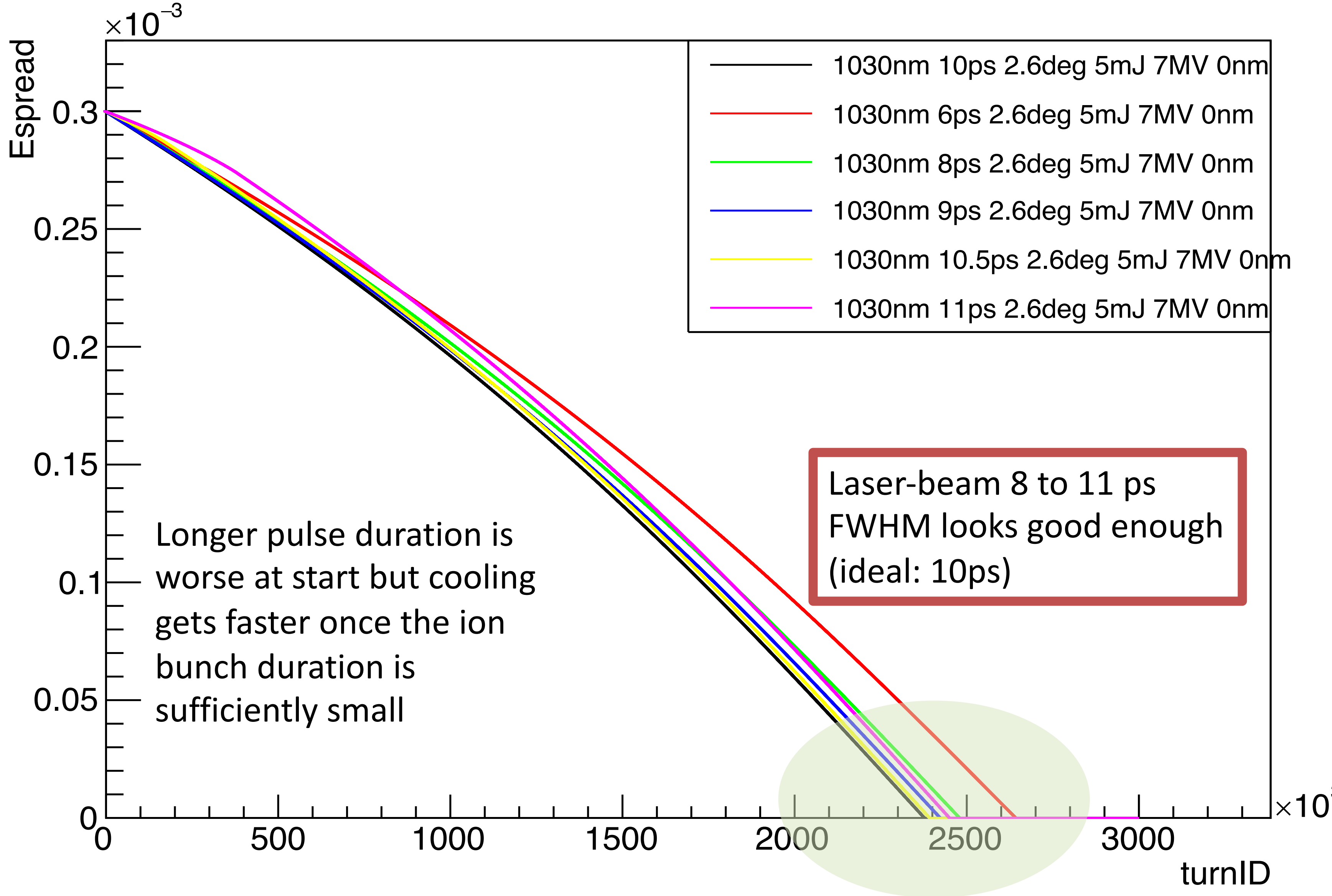
Motivation for a dynamical study

Previous plots are averaged over the whole ion bunch population, but…



Interaction probability heavily depends on where the ion is located in the bunch phase-space…

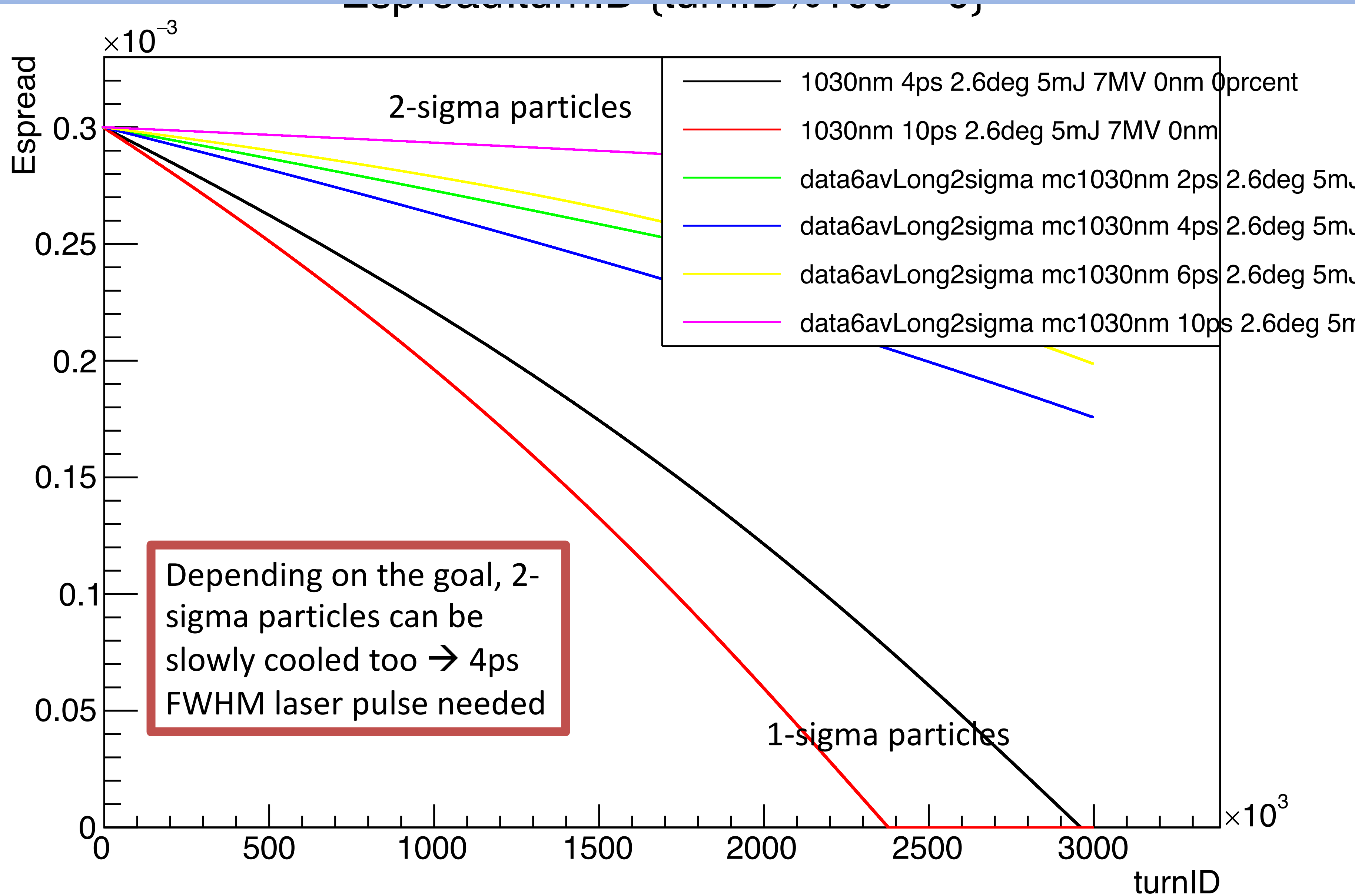
Dynamical aspects: 1-sigma particle



Longer pulse duration is worse at start but cooling gets faster once the ion bunch duration is sufficiently small

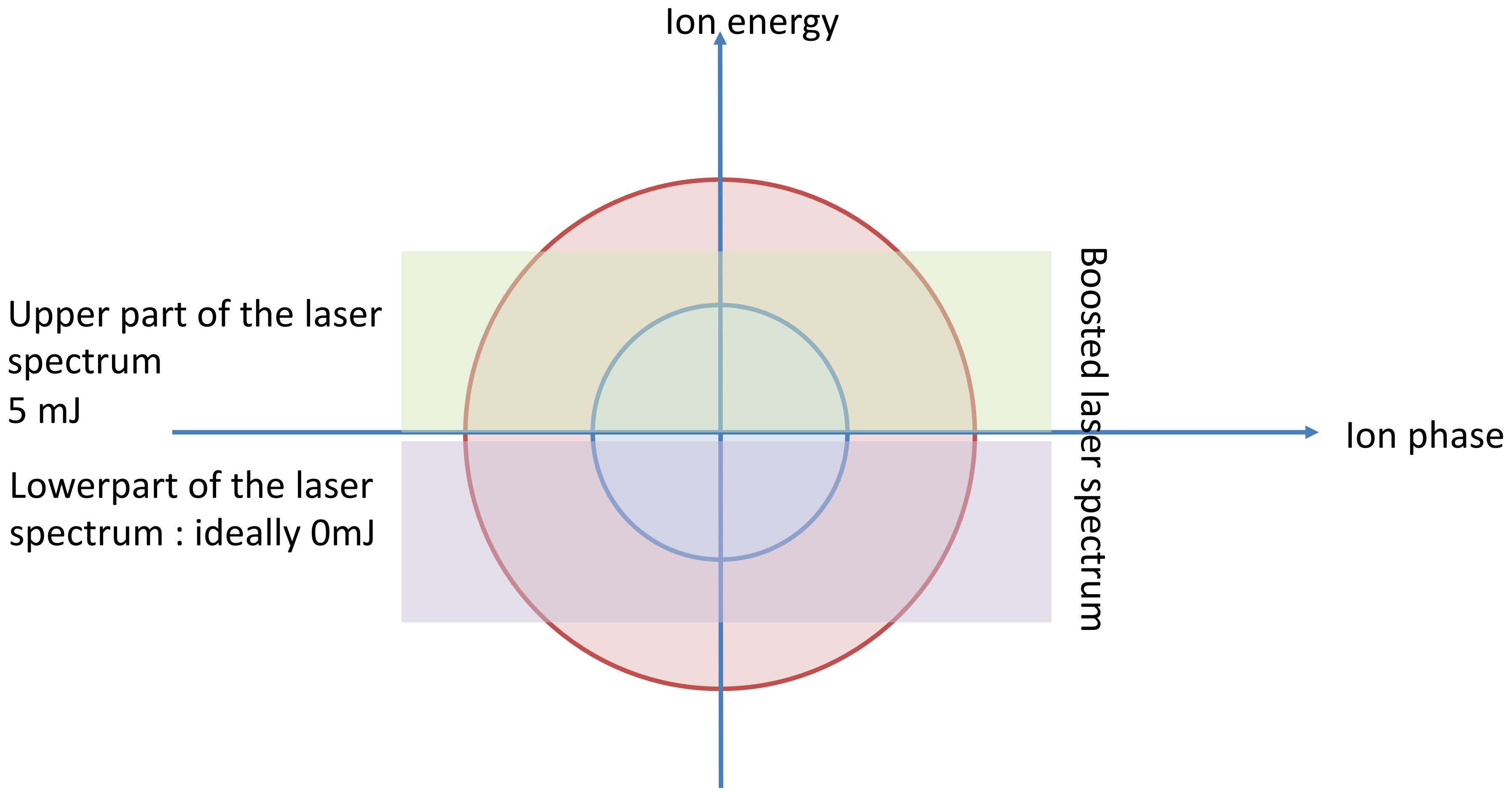
Laser-beam 8 to 11 ps FWHM looks good enough (ideal: 10ps)

Dynamical aspects: 2-sigma particles



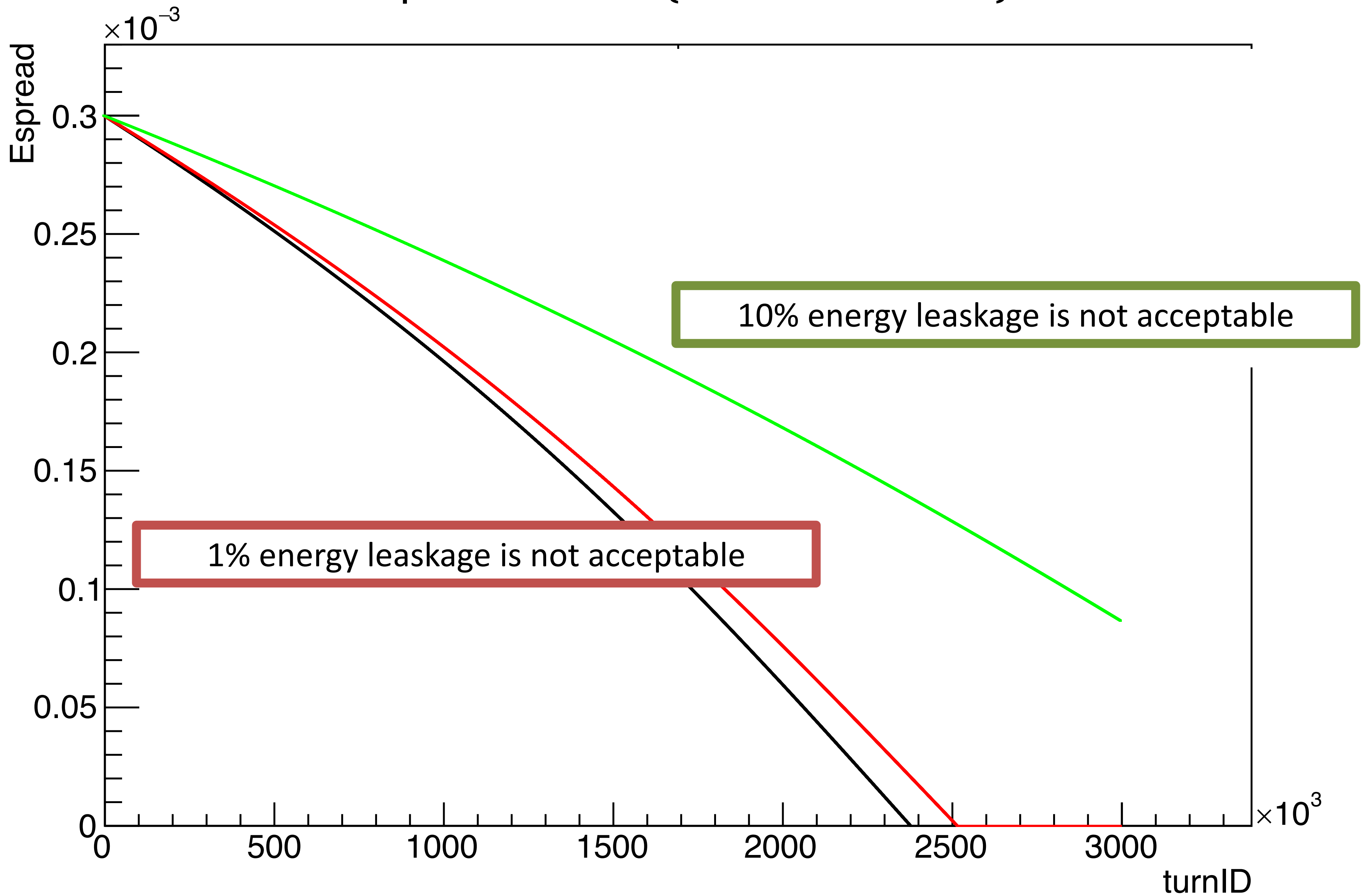
Tolerancing the laser spectrum

Previous plots are assuming.a perfectly flat spectrum, but…



In reality there will be some energy leakage into the lower part of the spectrum

Tolerancing the laser spectrum



Conclusions

excitation probablity varies from 7% to 20% (including saturation effects) for ion bunch durations from 400ps to 10ps.

Ideal laser bunch transverse size is unfortunately out of reach in the case of a FPC

Ideal laser bunch duration increases with decreasing ion bunch duration (i.e. while cooling occurs)

>63% of the particles can be 'cooled' wihtin a minute
>95% of the particles see 30% reduction of energy spread within a minute if the laser pulse duration is reduced

↓

Design a laser-system, including a FPC, with 1.5mm to 2mm waist at interaction point

Allow for tuning of the lasaer-beam duration between 2 and 12 ps (RMS gaussian)

1% energy leakage in the lower part of the spectrum is not an issue