H- Injection into PS2 and Laser Stripping

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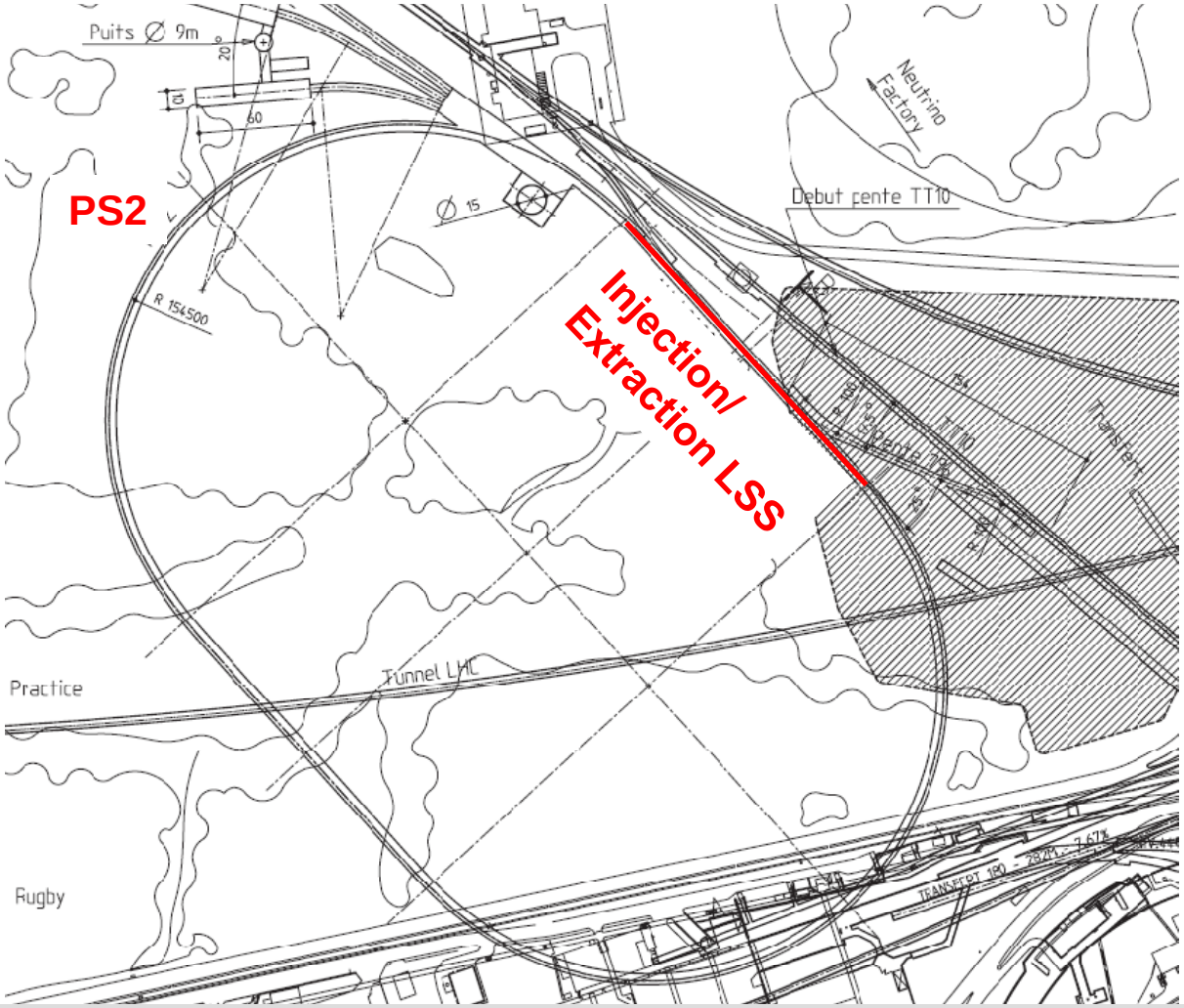
with a lot of input from V.Danilov and D.Johnson

- PS2 - general considerations and injection insertion
- Laser stripping requirements
- H- injection concepts accommodating foil and laser stripping
- Our main concerns (at the moment!)

Brief introduction to PS2

Injection/extraction straight

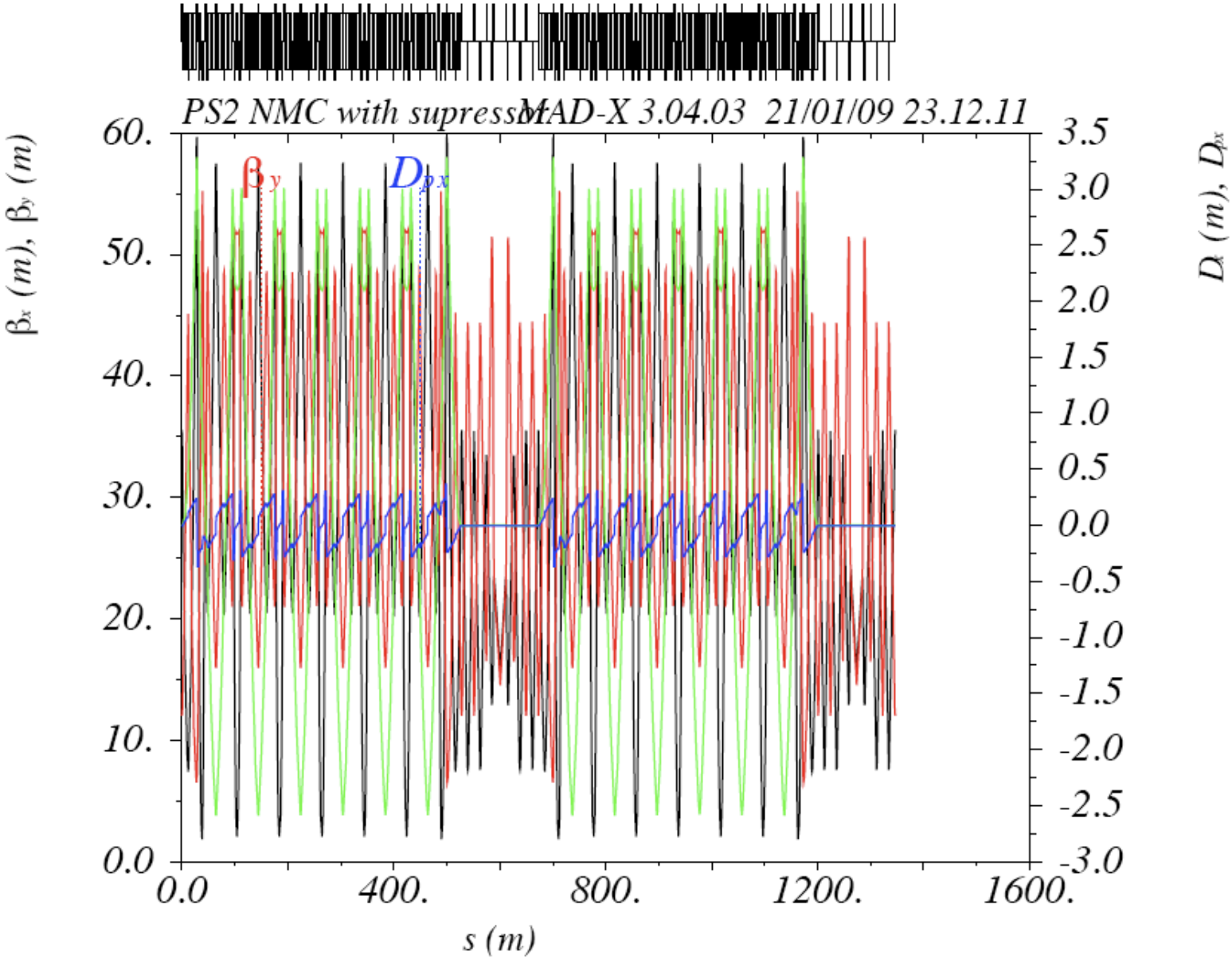
- PS2 with racetrack geometry (3-fold symmetry also under discussion)
- Assume all injection and extraction systems in one long straight section



PS2 Parameters

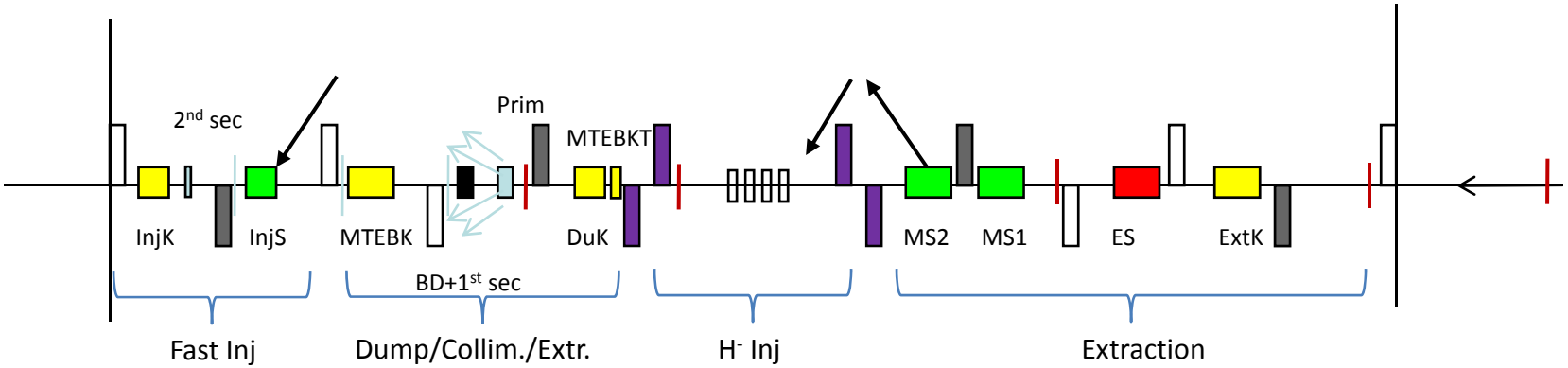
Parameter		
Injection kinetic energy	[GeV]	4
Extraction kinetic energy	[GeV]	~ 50
Circumference	[m]	1346.4
Transition energy	[GeV]	imaginary, adjustable
Maximum bending field	[T]	< 1.7
Maximum quadrupole gradient	[T/m]	< 17
Maximum beta functions	[m]	< 60
Maximum dispersion function	[m]	< 6
Beam power at injection	kW	50
Maximum injection inefficiency	%	5
Relativistic beta at injection		0.98
Relativistic gamma at injection		5.26

PS2 Lattice


PS2 NMC with supressMAD-X 3.04.03 21/01/09 23.12.11
βx (m), βy (m)
Dx (m), Dpx
βy
Dpx
60.
50.
40.
30.
20.
10.
0.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
0.0
400.
800.
1200.
1600.
s (m)

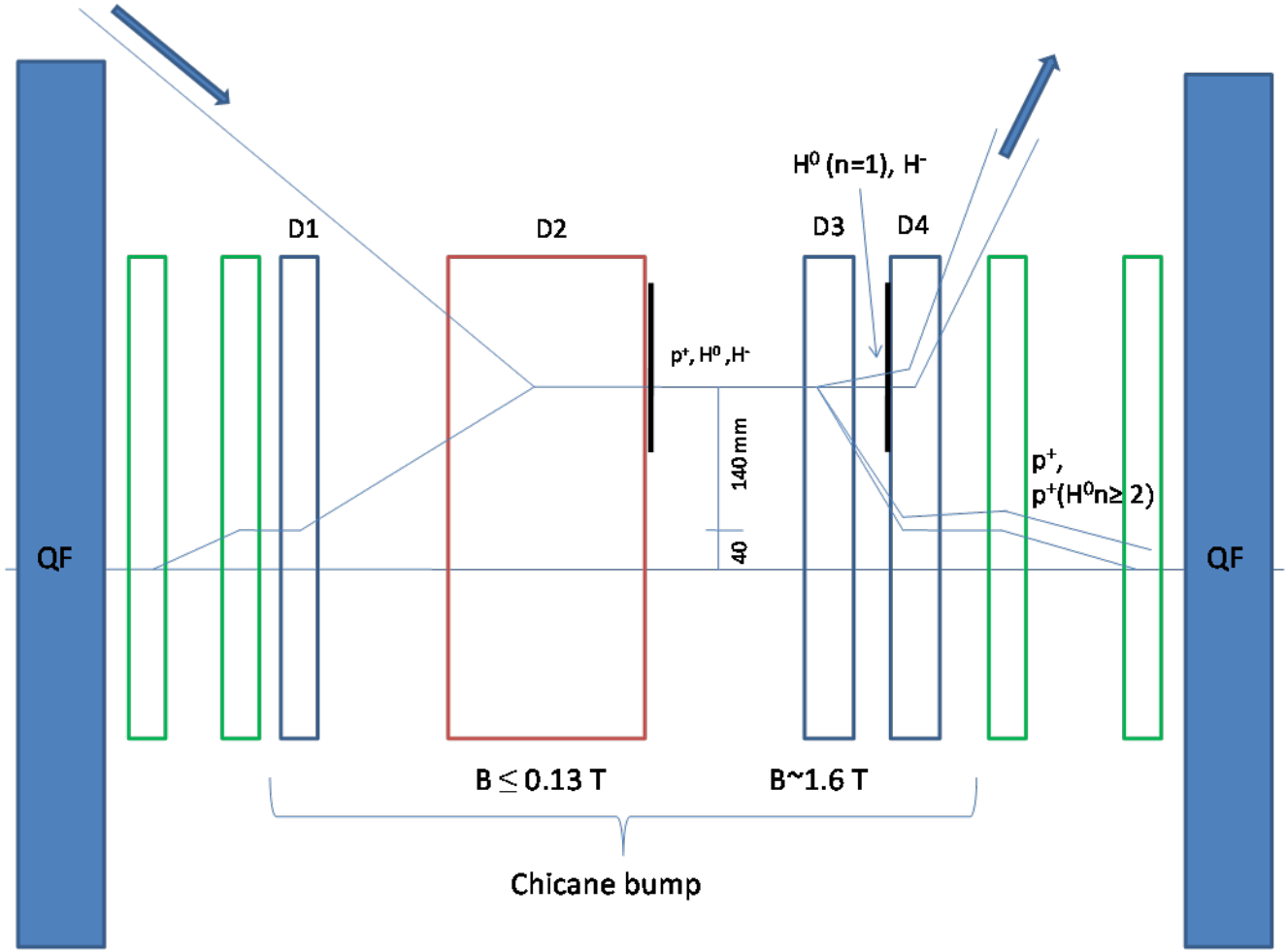
LSS Concept

- Beam Transfer Systems:
  - Fast injection for protons until H- and ions
  - H- injection with foil and laser stripping → two different optics needed
  - Fast, slow and low loss extraction
- Constraints:
  - 145 m length
  - 90 deg phase advance in the FODO cells
  - long drift to house H^- → Triplet in the centre
  - enlarged quads with special coil window design (in purple, light means to be decided)



- 4 GeV injection energy
- >140 m bending radius to avoid Lorentz stripping losses > 0.1 W/m

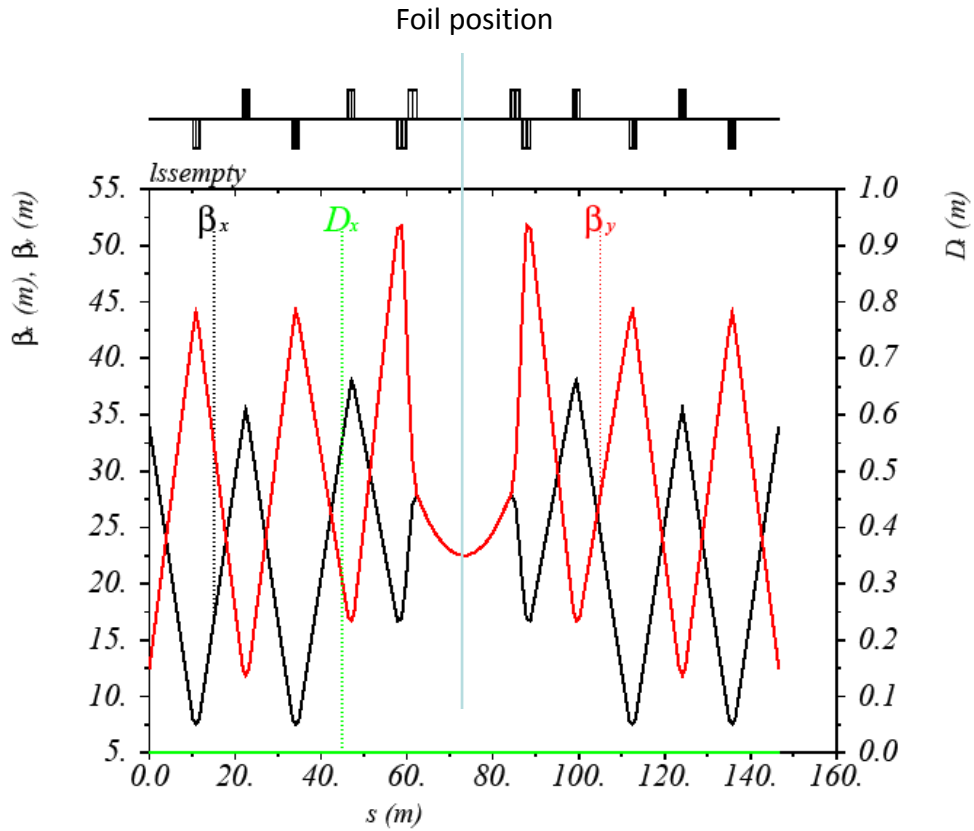
Triplet version: H- multi-turn, 4.0 GeV - based on FNAL concept



Long triplet drift (~22m) accommodating all elements

Requires space for 2 FODO half-cells for h- injection system

LSS Optics – Foil Stripping



Minimisation of foil width by a deliberate mismatch of the optics parameters between injected and circulating beam gives at the waist:

Machine parameters:
$\alpha_{x,y} = 0$ and $\beta_{x,y} \approx 22.5$ m

Injected beam parameters:

$\alpha_{x,y} = 0$ and $\beta_{x,y}$ at least 10 m

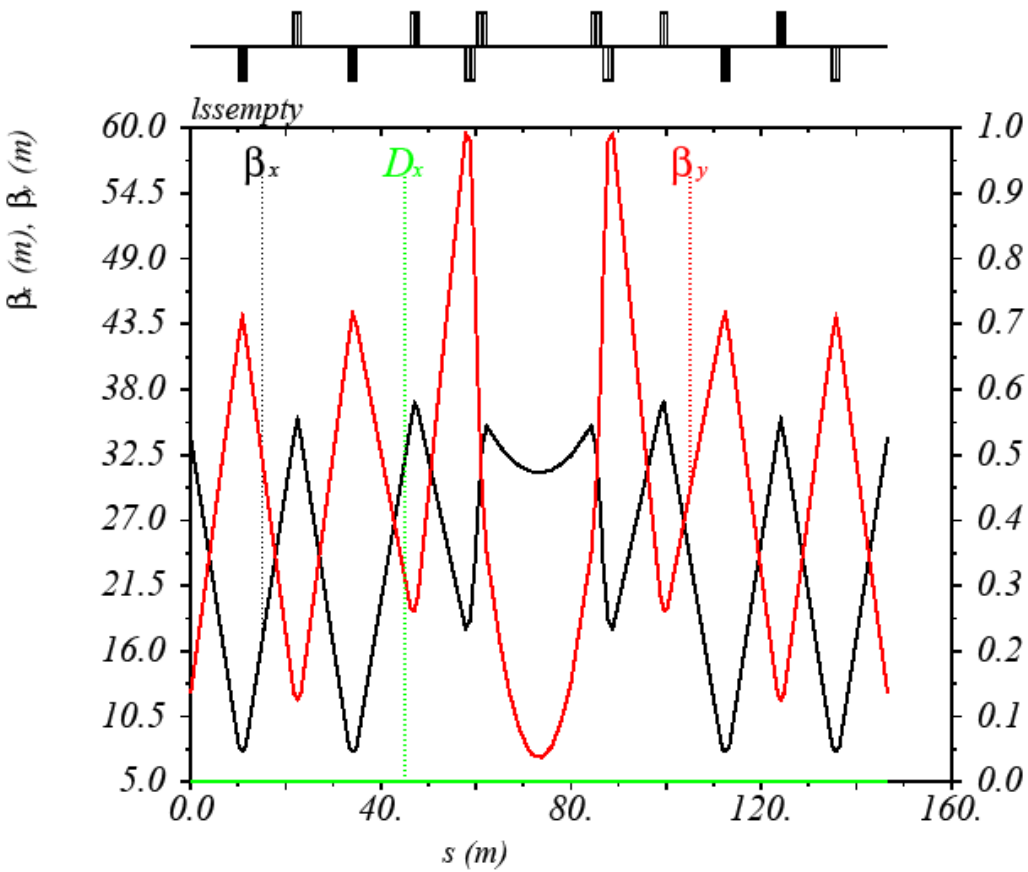
Laser stripping for H- injection into PS2

Laser stripping

- Baseline scheme:
  - Step 1: remove loosely bound electron from H- with strong magnet (~2T)
    - Do this in vertical plane to avoid increasing spread in x'
  - Step 2: resonant excitation of n=1 to n=2 (or n=3) transition with high-power laser
    - Based on Adiabatic Rapid Passage (ARP) - sweep resonant frequency across transition frequency – can result in population inversion (don't need to ensure exactly ½ Rabbi period)
  - Step 3: remove excited electron with another strong magnet (~2T)

- Alternative schemes
  - A scheme with photo-dissociation as first step seems interesting for PS2
  - Other possibilities?

LSS Optics – Laser Stripping



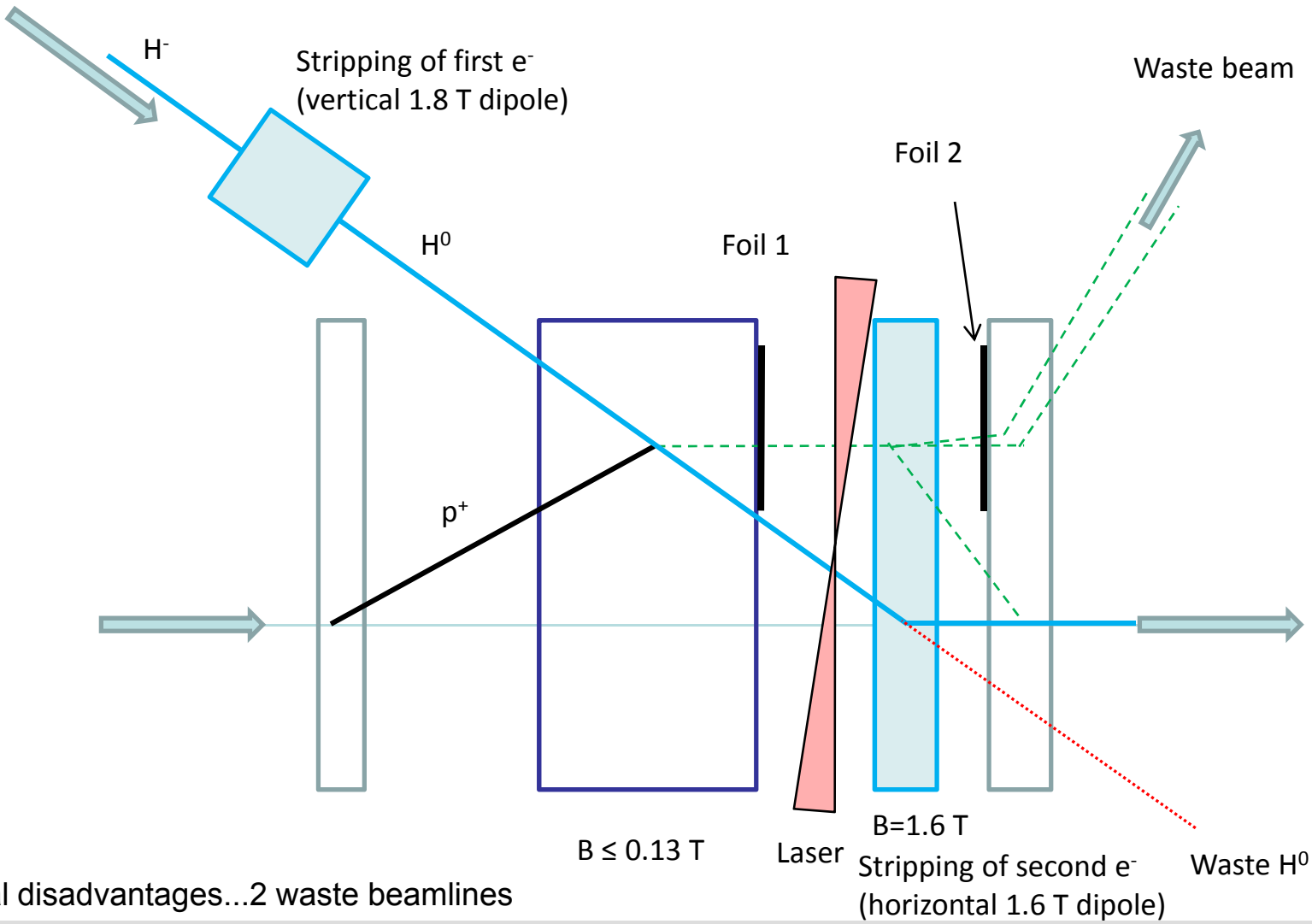
Laser peak power is proportional to vertical injected beam size if the beam-laser interaction is horizontal

⟹ reduce vertical beam size as much as possible for laser stripping LSS optics (assuming minimising betatron mismatch)

Obtain 7m β_y at waist…~10m at IR

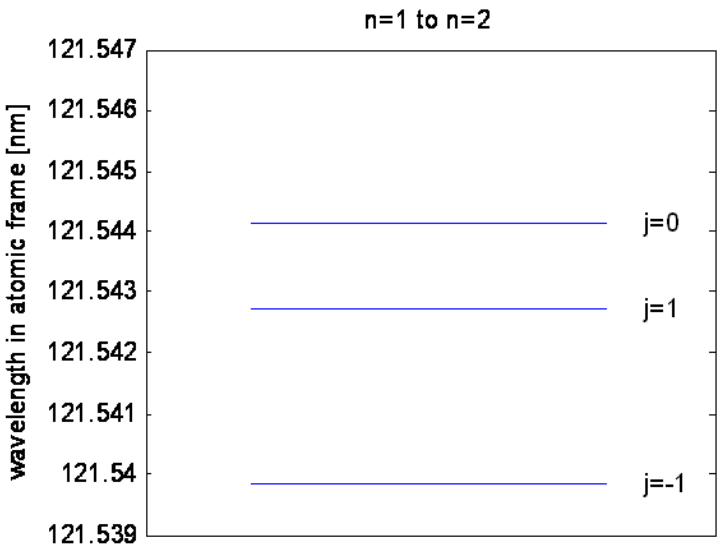
Have then about 1 mm σ_y for ~matched injection parameters

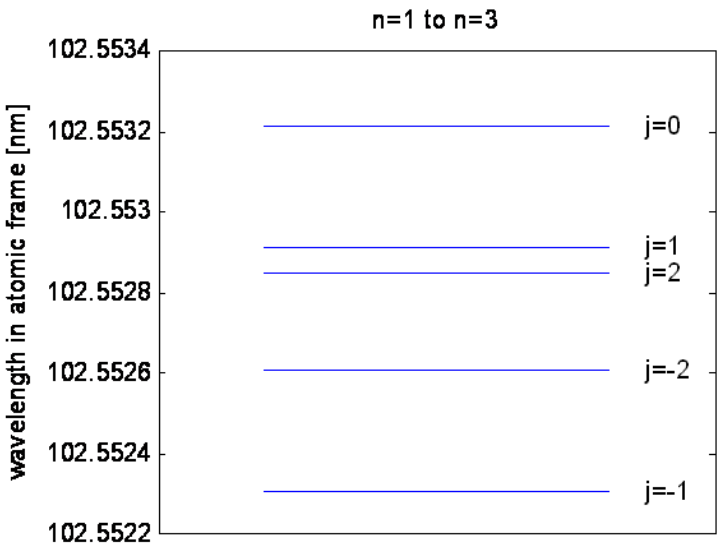
Combined chicane for foil + laser (4 and 3-bump respectively)



Several disadvantages...2 waste beamlines

Energies and wavelengths (for 4 GeV H^- beam)



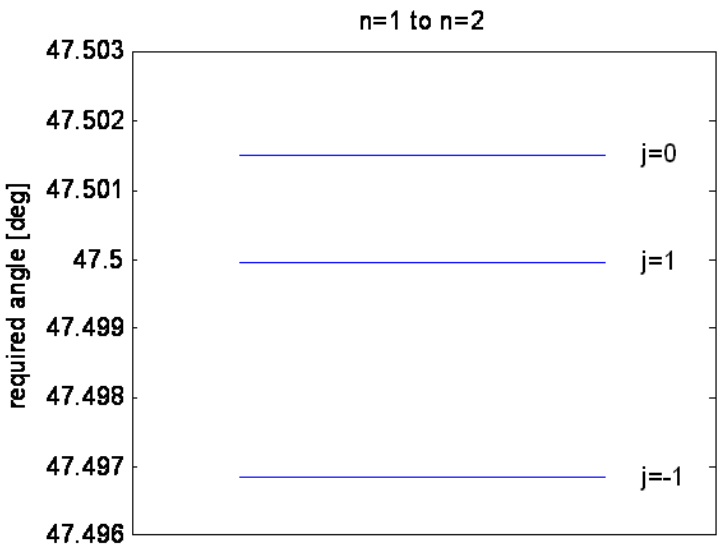


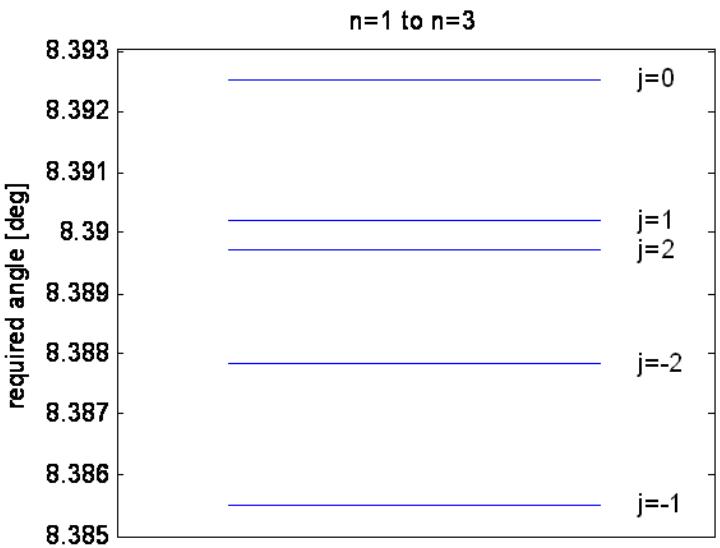
- Need 10.2 eV photon, or 121.542 +/-0.002 nm for *n=1* to *n=2* transition
- Need 12.1 eV photon, or 102.553 +/-0.001 nm for *n=1* to *n=3* transition

Angles between laser & beam

$$f_0 = \frac{f_s}{\gamma\left(1+\beta\cos\theta_0\right)} \qquad \theta_0 = a\cos\left(\left[\frac{f_s}{\gamma f_0}-1\right]\Big/\beta\right)$$

Where f_s is the frequency of the laser and f_0 the resonance





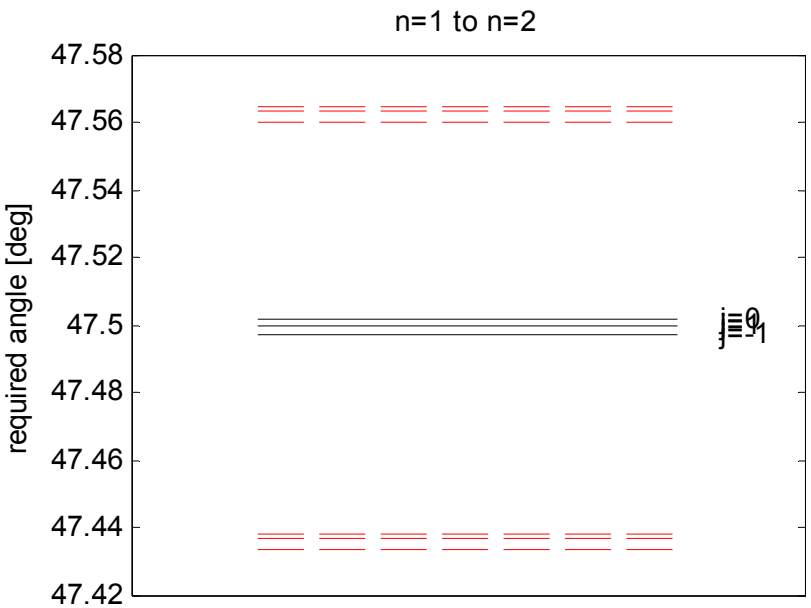
- Need 47.499 +/-0.003 deg for *n=1* to *n=2* transition
- Need 8.389 +/-0.004 deg for *n=1* to *n=3* transition

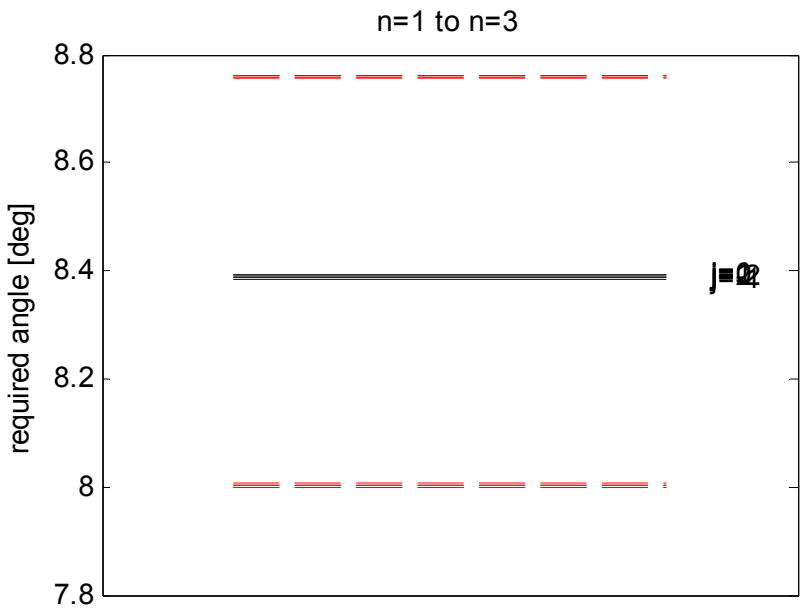
Doppler spread

Spread of momenta in the beam gives different resonant frequencies….0.046 % energy spread (rms) + jitter (0.46 and 1.37 MeV) $dp/p = 1/\beta^2 * de/e$, so for PS2 injection total dp/p = 0.048% (not including any longitudinal painting!)

$df/f_0 = d\lambda/\lambda_0 \propto dp/p * \beta(\beta+\cos\alpha)/(1+\beta\cos\alpha)$

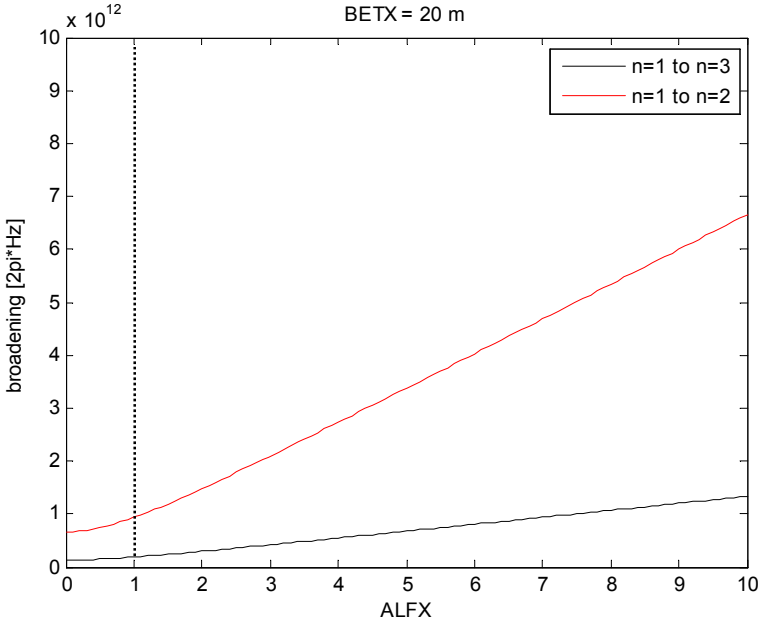
Then for 1 sigma spread of $\delta p/p$ ~4.8e-4, the wavelength spread required is:
- 0.06 nm for *n=1* to *n=2* transition (cf +/-0.002 for fine-structure), or 47.5+/-0.07 deg
- 0.05 nm nm for *n=1* to *n=3* transition (cf +/-0.001), or 8.4 +/-0.4 deg

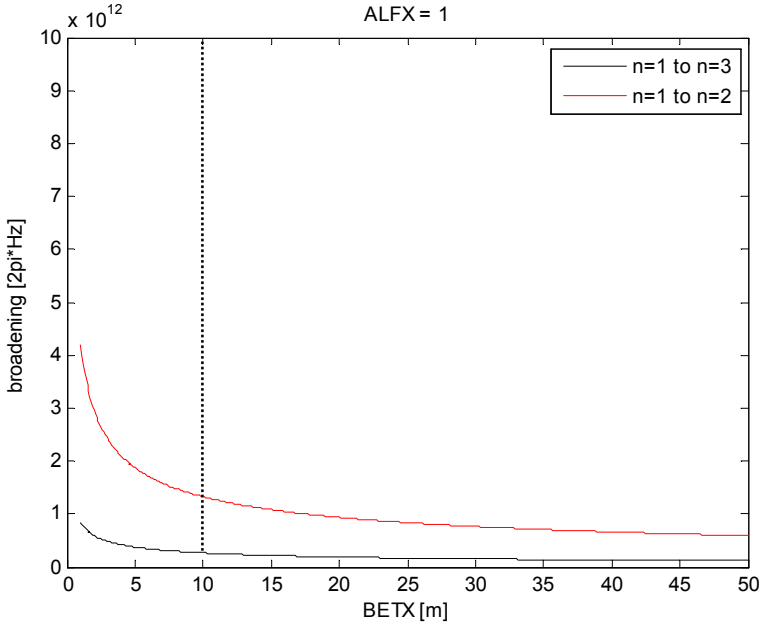




Frequency spread from beam αβ

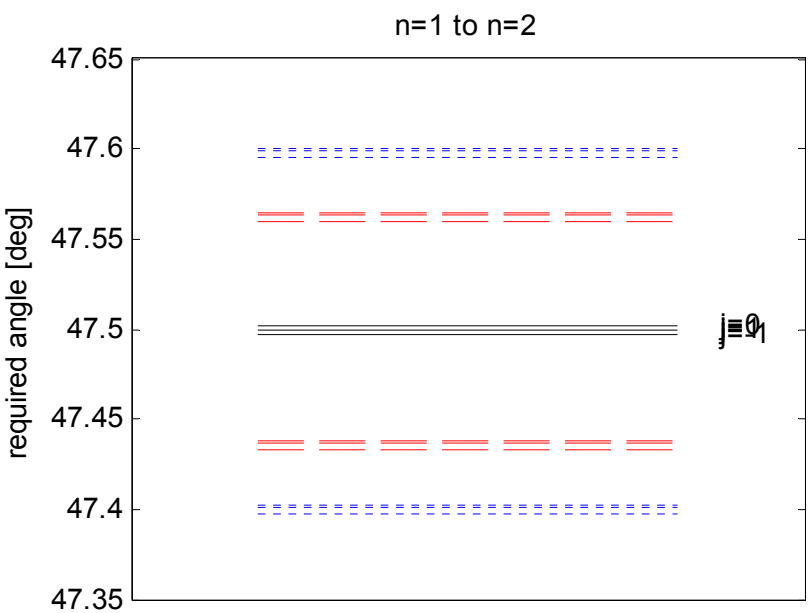
- Frequency spread given by $$\frac{\partial\omega}{\omega} = \frac{-\beta\sin\alpha\cdot\delta\alpha}{1+\beta\cos\alpha}$$
- Note that this is the same broadening as transit time broadening (caused by finite length of interaction region which causes a spread in the frequencies given by the Fourier transform of the finite-duration laser pulse).
- Need to keep alpha_X below about 0.5-1.0, and beta_X above about 10m
- Easier for n=1 to n=3 transition.

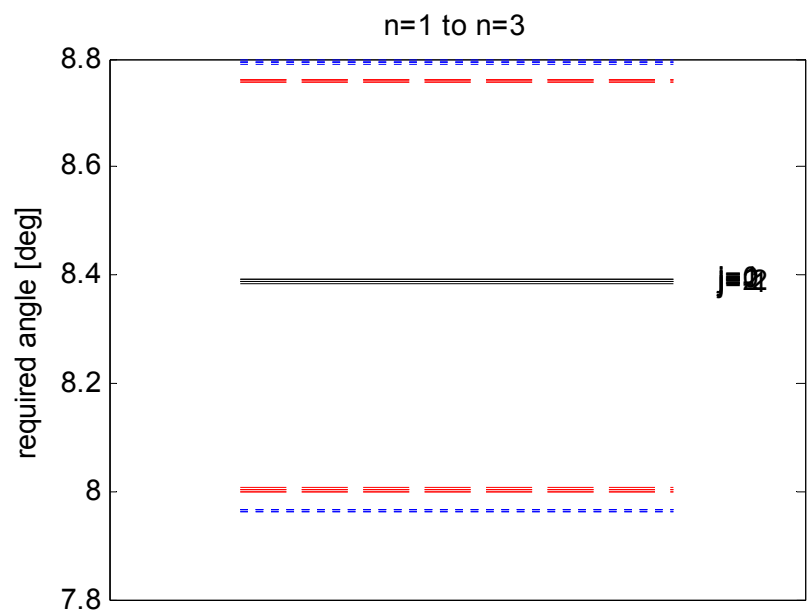




Frequency spread from beam αβ

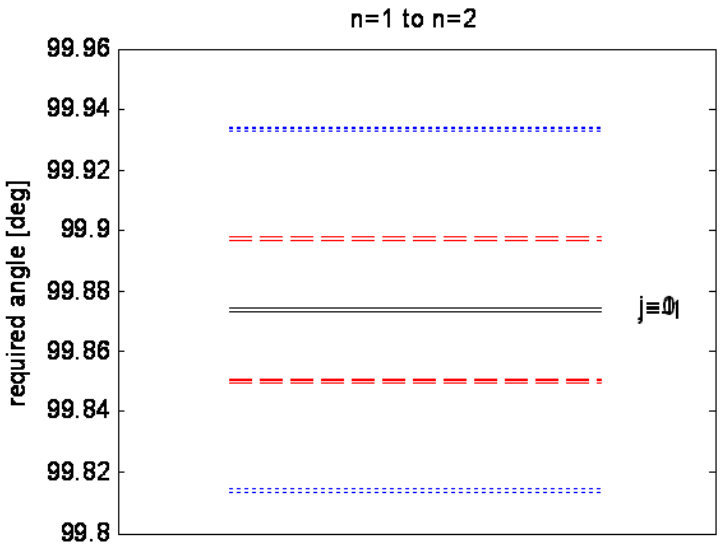
- Results in further increase in angles needed – illustrated for 10 m betx and 1.0 alfx (somewhat pessimistic)
  - for *n=1* to *n=2* transition 47.5+/-0.1 deg
  - *n=1* to *n=3* transition 8.4 +/-0.45 deg

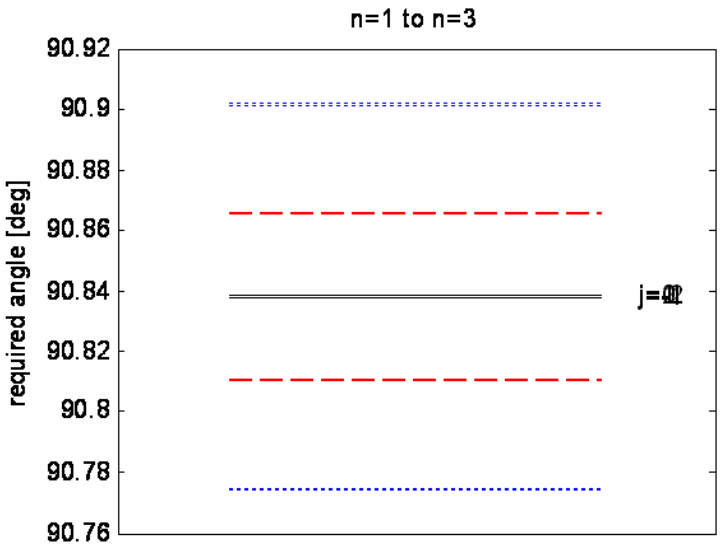




Alternative: 2nd harmonic Nd:YAG

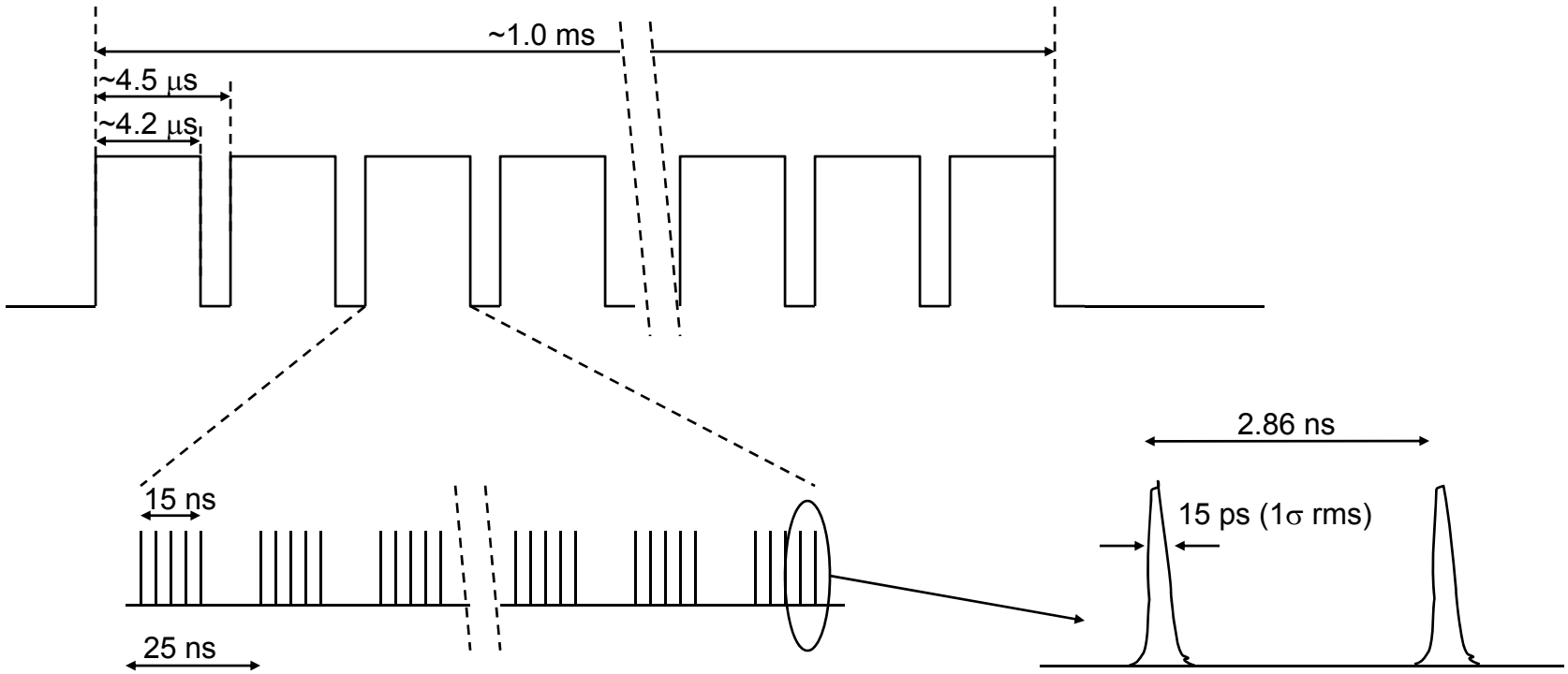
- 532 nm (green) – “easy” to produce with high efficiency?
- 90.8 degrees for n=1 to n=3 transition
  - Geometrically very nice!
  - No laser beam passage through dipole coil
  - Can get close to the magnet edge (few cm?)
- Disadvantage of higher (fundamental) laser power required....
- Laser power to saturate also turns out to be much higher (later slide...)





Beam temporal structure

- Macropulse injection over ~1ms (200-300 turns injected)
- Chop in short gaps for extraction kicker rise-time
- SPL microbunch structure at 352 MHz…15 ps (rms) spaced by 2.86 ns



Laser power needed to saturate the transition

- Based on formulae in Slava's paper* ….

$$P_{peak} = \frac{\ln(1/\delta)\hbar^2 \varepsilon_0 c^2 \kappa \omega_0 h \sin\alpha}{2\mu_{1n}^2 \gamma (1+\beta\cos\alpha)^2}$$

where $\delta << 1$ is the ratio of unexcited to excited atoms, *h* is the vertical beam half-size, $\omega_0=\gamma(1+\beta\cos\alpha)$ is the laser frequency in the atomic rest frame, α is the angle between laser and atomic beam, $\kappa\approx 6\delta\gamma/\gamma$ is the full relative frquency change along the beam path, and μ_{1n} is the dipole transition coefficient

- Calculations by Slava at HB'08 showed we need ~0.5 MW peak power for PS2 with 4GeV and 1064 pumping the n=2 level….but we assume 1.5 MW due to larger h and take an operational margin of factor 3 to give 4.5 MW
- Need this power level for 1 ms every 2 s…average power is then 2.25 kW
- Mode-locked train of laser pulses matched to 15 ps rms microbunches, with 2.86 ns spacing would reduce average power to 71 W (cover ±3 sigma)
- Interaction region inside Fabry-Perot cavity with Q_c = 1000 gives 2.25 W average power
- Mode-locking and Q_c 1000 cavity together would give 71 mW average power

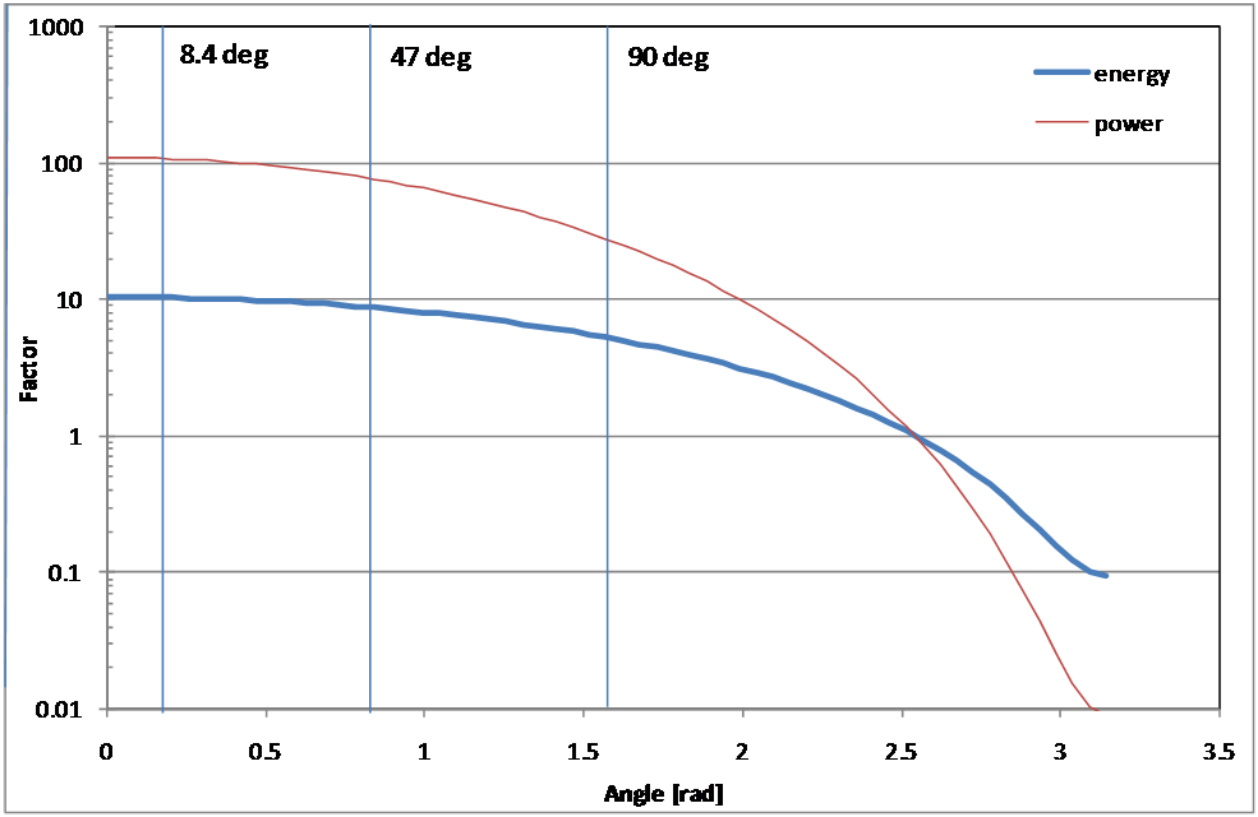
*V.Danilov et al, Phys. Rev. ST Accel. Beams 6, 053501 (2003)

Characteristics relevant for the laser system

Parameter		n=2	n=3	n=3	n=4
Wavelength	nm	1064	1064	532	532
Laser/H- angle	deg	47.50	8.39	99.84	87.69
Angular spread	deg	±0.10	±0.42	±0.06	±0.07
Peak power (single pass)	MW	4.5	1.3	13.9	43.3
Average power (single pass CW)	kW	2.25	0.6	7	22
Average power (mode-locking only)	W	71	20	220	681
Average power (Q_c=1000 CW only)	W	2.25	0.6	7	22
Average power (mode-locking, Q_c = 1000)	mW	71	20	220	681
Vertical laser beam height (1 σ rms)	mm	1.0	1.0	1.0	1.0
Horizontal laser beam width	mm	?	?	?	?
Laser stability	%	<20	<20	<20	<20
Laser availability	%	~99	~99	~99	~99
Laser repetition rate (max)	Hz	0.5	0.5	0.5	0.5

Includes factor 3 operational margin in laser power

Influence of interaction angle on effective laser power



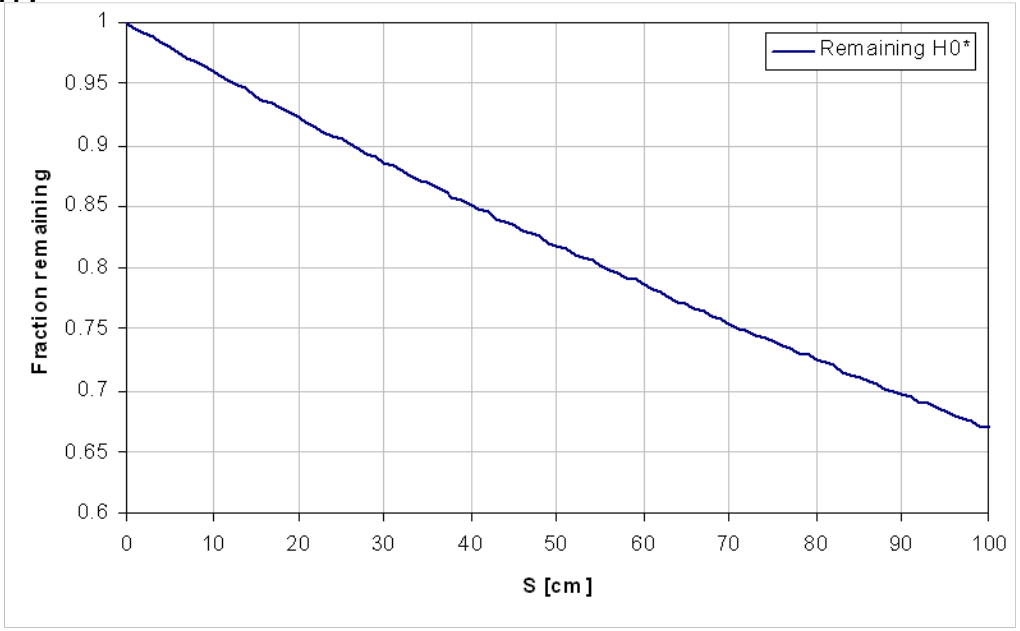
- Clear advantage to low angles….factor of 2 or 3 gain evident from previous table

Dispersion matching for PS2?

- Main issue seems to be very high laser power needed to saturate the transition - peak powers of ~ few MW over ~1 ms injection time
- Dispersion tailoring as proposed by Slava *et al*. would help – arrange DPx to cancel to first order the Doppler broadening (angle at interaction point matches angle needed for resonant excitation)
  - Could gain factor 10-20 in laser power
  - But needs very large DPx of about 2.0 rad!
  - Emittance growth will be an issue for us with LHC beam of about 2.5 μm ε_x normalised (not such a concern for high-power accumulator rings)
  - Max tolerable mismatch is ~0.2 m Dx and 0.02 rad DPx (~zero dispersion in injection region) for factor 2 in emittance

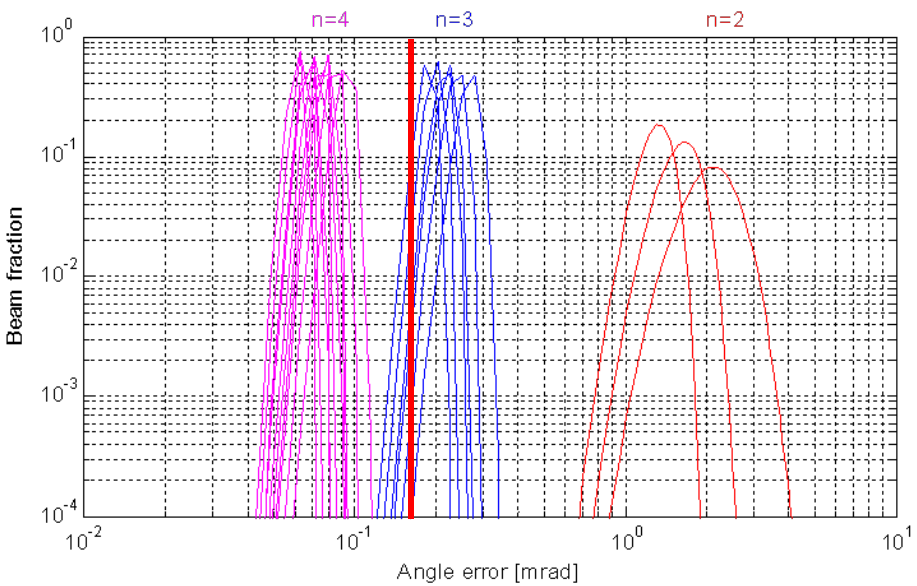
Spontaneous decay between laser and stripping dipole

- Decay from n=2 depends on path length – assuming lose 0.4% per cm, can have max 10 cm drift to stripping dipole to keep efficiency >96%...
- Ideally would like to make laser interaction region in strong field region of dipole
  - Immediate stripping to p+ minimises angular spread
  - No spontaneous decay issue
  - But…what about resonant excitation in strong magnetic field??? Stark splitting and broadening of levels - will increase laser power required to saturate transition?

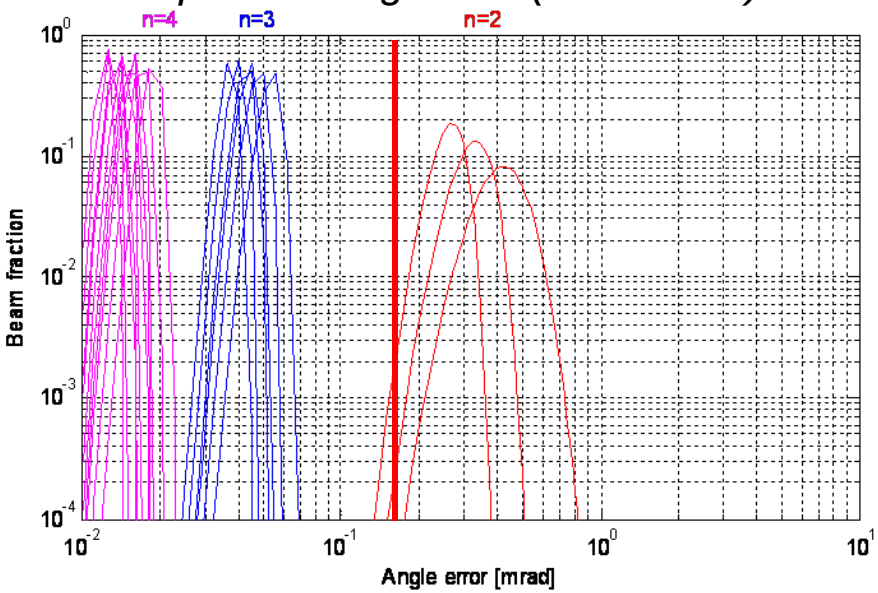


Angular spread of field-stripped p+

- Integration of remaining dipole field at stripping point vs total B.dl
- Large angular spread for n=2 state
  - Several mrad angles in distribution – cf $\sigma_{x'} \approx \sqrt{\varepsilon/\beta_x} \approx \sqrt{3\times10^{-6}/(5.16\times20)} \approx 0.17 mrad$
- About 0.3 mrad for n=3…this looks more OK
- May need to improve fringe field shape to get to 0.05 mrad – technical feasibility to be investigated



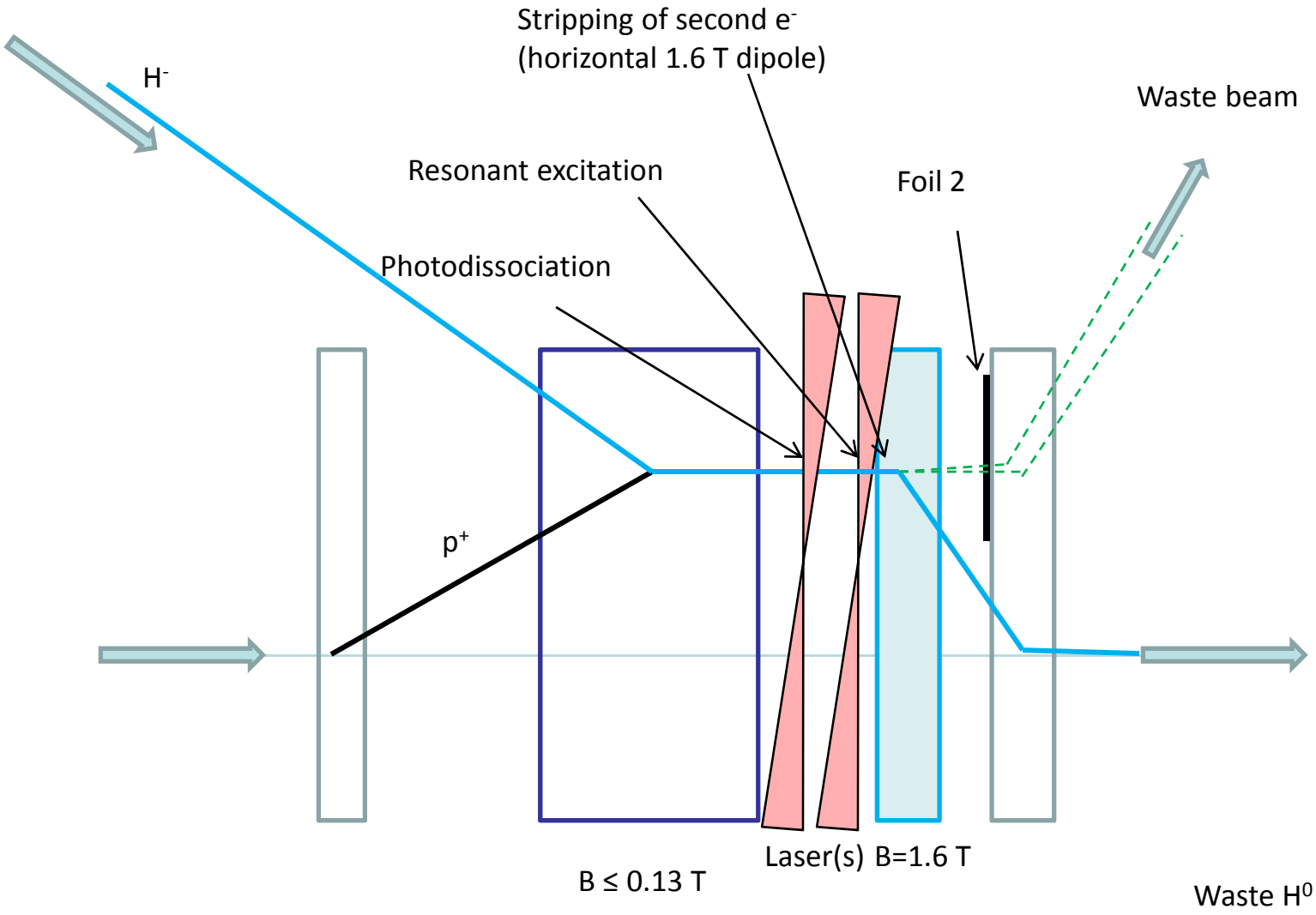
Improved fringe field (x5 shorter!)



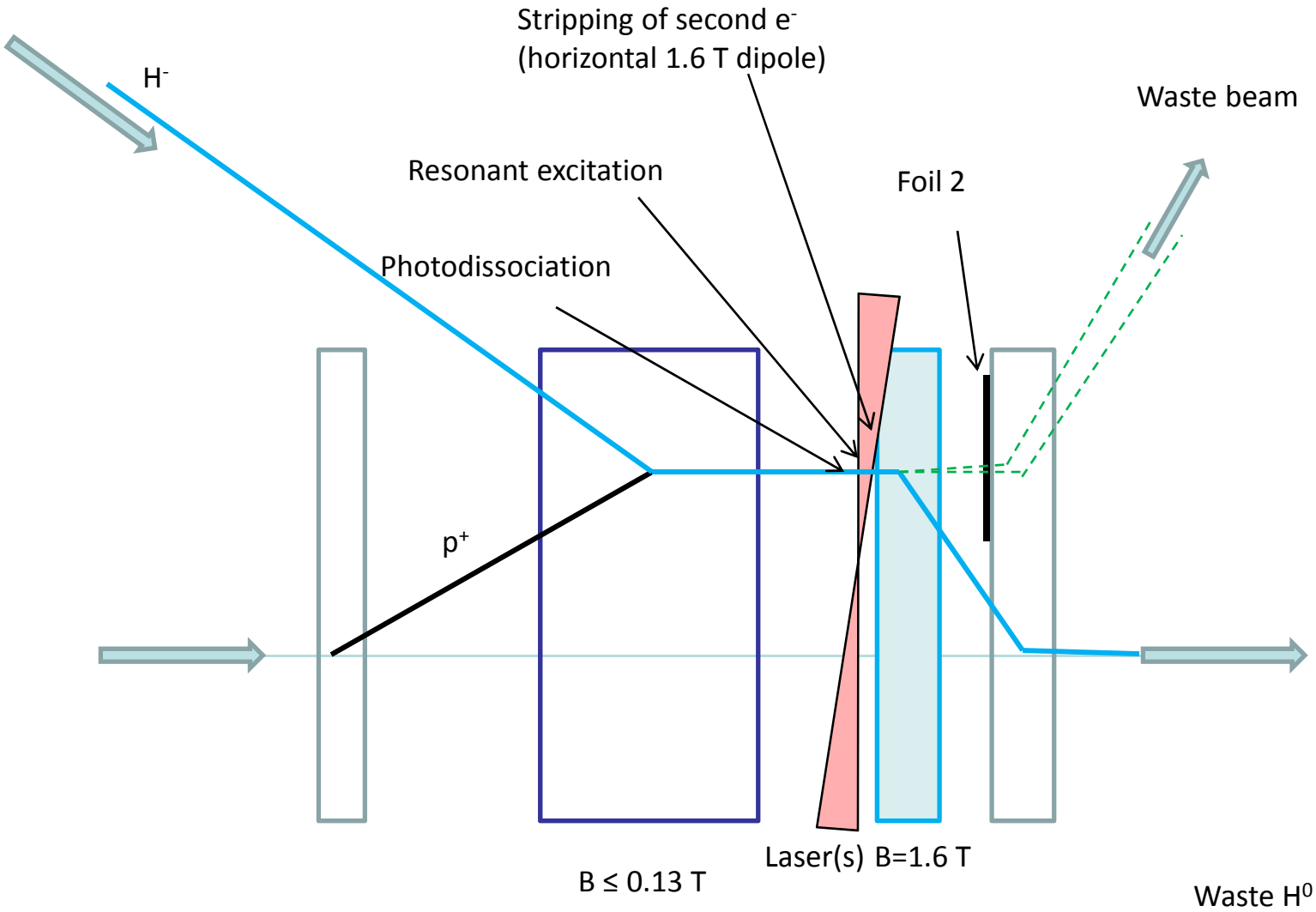
Alternative concept for PS2?

- Using vertical dipoles to strip first electron poses us some problems with the injection geometry....
- Removal of first e- with laser photo-dissociation?
  - Peak of dissociation cross-section is at ~1.6 eV....141° incidence for 1064 nm
  - Resonant excitation of H^0 to n=2 or n=3 level
  - Lorentz strip remaining e- in 3rd chicane dipole
- Big advantage in geometry for PS2 –same injection and dump beamlines
  - No extra vertical chicane in injection region
- What laser power is needed to saturate the dissociation process?
- Can the same laser cavity be used as for the resonance excitation, using the 180° – α incidence angle photons????

Combined chicane for foil + laser – alternative?



Combined chicane for foil + laser – alternative?



Combine steps 2 and 3 into same optical cavity ???

Some questions

- Is there a better concept for combining foil and laser insertion?
  - Can both the 3 bump and the 4 bump be closed with respect to dispersion?
  - Waste H0 beam from laser is only 40 mrad wrt orbit - septum needed?
  - Is photodissociation as step 1 feasible?
- Laser IR issues
  - What determines horizontal beam size –distance from focus and angular spread?
  - Concentric, confocal or concave-convex recycling cavity?
  - Is the transit time broadening the same as spread from beam α? Or does this need to also be taken into account separately?
- Laser power
  - DPx of about 2.28 given by $-(\beta + \cos\alpha)/\sin\alpha$ is required to cancel Doppler broadening – this looks unfeasible but is there any way to make this work?
  - Feasibility of mode-locked pulse train in high Q cavity?
- Alternatives…?

Characteristics relevant for the laser system

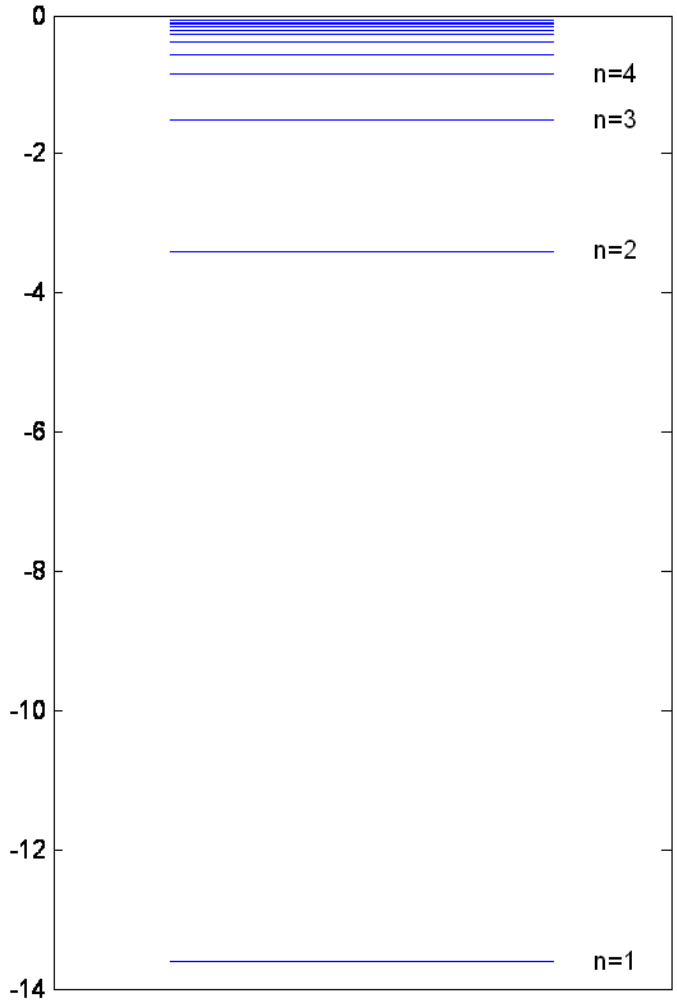
- Wavelength: 1064 (532 nm does not look feasible)
- Peak power: ~ 5 MW
- Rep rate: 0.5 Hz
- Macropulse length: ~1 ms
- Linac bunch structure : 15 ps rms separated by 2.86 ns (352 MHz)
- Laser-H- beam interaction region geometry (beam size, angular spread)?
- Temporal profiles : Need ~rectangular pulse in time, for about 90 ps
- Stability requirements (shot-to-shot jitter, long term, …): 10-20% OK?
- Ionising radiation environment constraints?: Yes
- Availability: 99%
- Associated diagnostics?
- Any laser beam delivery constraints (geometrical): Minimum length of FP cavity?
- Laser polarisation?
- Spatial profile?

Summary

- Assuming laser stripping 3 step process: magnet – laser – magnet
  - Starting to evaluate feasibility with SNS & maybe future LARP collab.
- Checking implications of different schemes
  - Nd:YAG fundemental: ~47° incidence for n=1 to n=2, 8° to n=3
  - 2nd harmonic would give ~91° for n=1 to n=3…but power very high!
- Big issue seems to be laser power required
  - Dispersion tailoring will be tough/impossible (2.0 rad DPx needed! Max tolerable mismatch is ~0.2 m Dx and 0.02 rad DPx)
  - Smaller vertical beam size not obvious (~10m β_y realistic)
  - Feasibility of external cavities, mode-locked lasers, …(still have several MW peak power of laser light circulating in the cavity….optics…?)
- Insertion concept with foil and laser could be improved…
- Possibility of photo-dissociation for first step proposed - should be further investigate wrt feasibility

Fin

Hydrogen atom energy levels



eV	*n*	*j*
-13.600	1	0
-3.3998	2	-1
-3.4001	2	0
-3.4	2	1
-1.5111	3	-2
-1.5111	3	-1
-1.5112	3	0
-1.5111	3	1
-1.5111	3	2
-0.85	4	-3
-0.85	4	-2
-0.85	4	-1
-0.85	4	0
-0.85	4	1
-0.85	4	2
-0.85	4	3

$$E_{nj} = \frac{-13.6\ \mathrm{eV}}{n^2}\left(1 + \frac{\alpha^2}{n^2}\left(\frac{n}{j+\frac{1}{2}} - \frac{3}{4}\right)\right)$$

Including hyperfine splitting

n = 1,2,….

j = -(n-1), …0, …(n-1)

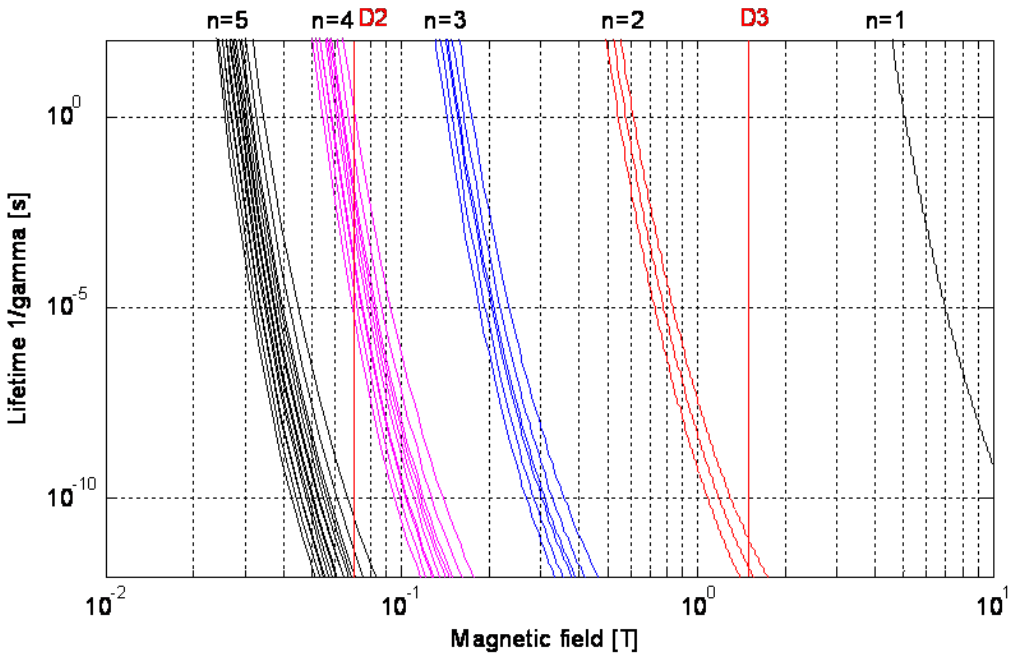
α = fine structure constant

Other ways to reduce required laser power?

- Smaller vertical beam size (sub mm) – optics feasibility???
  - Presently 1 mm (rms)
  - For PS2 cannot afford large emittance blow-up….limits mismatch in beta functions to about a factor of 4
  - Could possibly gain a factor of 1.5 to 2 at maximum in vertical beam size (need to check TL optics more carefully to be more precise)
- Mode-locking to linac 352 MHz frequency and recycling photons with FP cavity could reduce average power to something like 100 mW or below

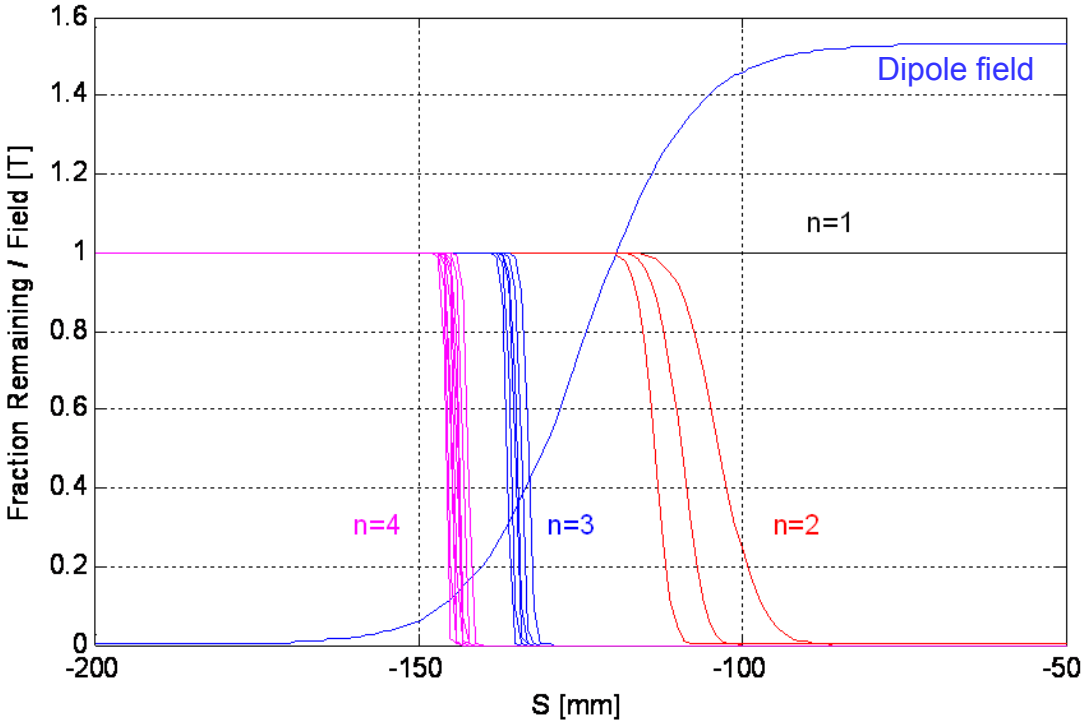
Excited H0 states and beam losses

- Arrangement of D2 and D3 fields to optimise excited H0 state lifetimes
  - Locate foil in D2 fringe field
  - Make field at foil ~0.07 T such that n=4 states survive but n>=5 are stripped immediately
  - Make D3 field ~2 T such that n=2-4 are stripped to p+ and join injected beam, while only n=1 survives as waste beam



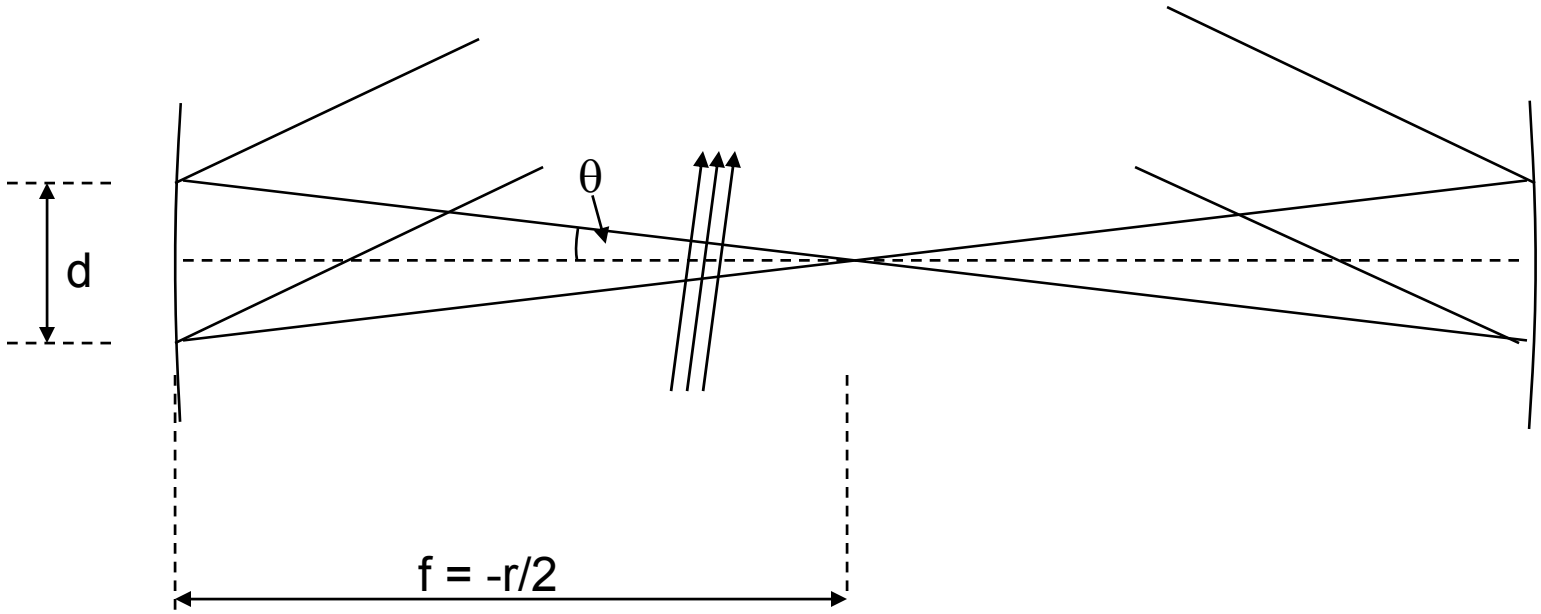
Decay lengths in D3 fringe fields – angular spread

- Numerical integration with representative dipole field shape (1.5 T)



Laser interaction region

- Considering a cavity made from 2 spherical mirrors



$\tan\theta = d/2 / f = -d/r$, and assuming a beam height d of 10 mm….

- for n=1 to n=2 transition, θ = 0.1 deg, so f = 2.86 m, l = 5.72 m
- for n=1 to n=3 transition, θ = 0.45 deg, f = 0.64 m, l = 1.28 m

Some questions / potential issues

- Can a D3 magnet with a very hard-edged field distribution be built?
- What is the angular spread from the D0 H- stripping magnet?
- Can a C type D3 dipole be built with the required aperture?
- Can both the 3 bump and the 4 bump be closed with respect to dispersion?
- D3 field needs to reverse between foil and laser – any issues?
- Waste H0 beam from laser is only 40 mrad - septum needed?
- Concentric, confocal or concave-convex recycling cavity?
- DPx of about 2.28 given by $-(\beta + \cos\alpha)/\sin\alpha$ is required to cancel Doppler broadening – this looks unfeasible but is there any way to make this work?
- Any possibilities to use chirped pulse techniques to match the Doppler broadening in the H^0 beam?
- What alternative schemes exists - second resonant step, multiphoton ionisation, lasrer to remove first e-, …
- Is the transit time broadening the same as spread from beam α? Or does this need to also be taken into account?