Gamma Factory Simulation Progress from Royal Holloway University of London

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BDSIM Beam Delivery Simulation

Overview

- Introduction to the laserwire work done by the RHUL group.
- Overview of laserwire diagnostics for negative hydrogen ions.
- Outline for the simulation functionality and its application on the Front End Test Stand (FETS).
- Applying the model to the SPS distribution.
- Motivating developing laser interactions for Beam Delivery Simulation (BDSIM).
- Summary and discussion.

Royal Holloway Lasers for Accelerators Research

- The Royal Holloway group has been active in the design and implementation of **laserwire** diagnostics for over a decade.

- For electron beams, a laserwire interactions via Compton scattering. Group electron beam laserwire installations include:
  - KEK ATF2 - demonstrated sub-micron resolution with mode-locked Nd:YAG ~2GW peak power.
  - DESY PETRA-II & PETRA-III – Chirp pulse amplification with photonic crystal fibre transport.

- For hydrogen ion beams, a laser interacts via photodetachment. Group hydrogen beam installations include:
  - CERN LINAC4 – principle demonstrated in prototypes at 3, 12, 50, 80, 100 MeV
    - Final system installed with fibre coupled, dual axis, dual station, with diamond detector.
  - (Rutherford Appleton Laboratory UK) FETS – Novel longitudinal laserwire in development.

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Example : LINAC4 Laserwire

- Preliminary simulations of H^- ion interaction with a Gaussian laser beam were developed to model a laserwire for diagnostics on LINAC4.

- The model was successfully applied to assess detector yield based on laser parameters.

- The predicted signal was validated by experimental data from LINAC4 over a range of energies.

- T Hofmann’s PhD thesis “Development of a laser-based emittance monitor for negative hydrogen ion beams.”

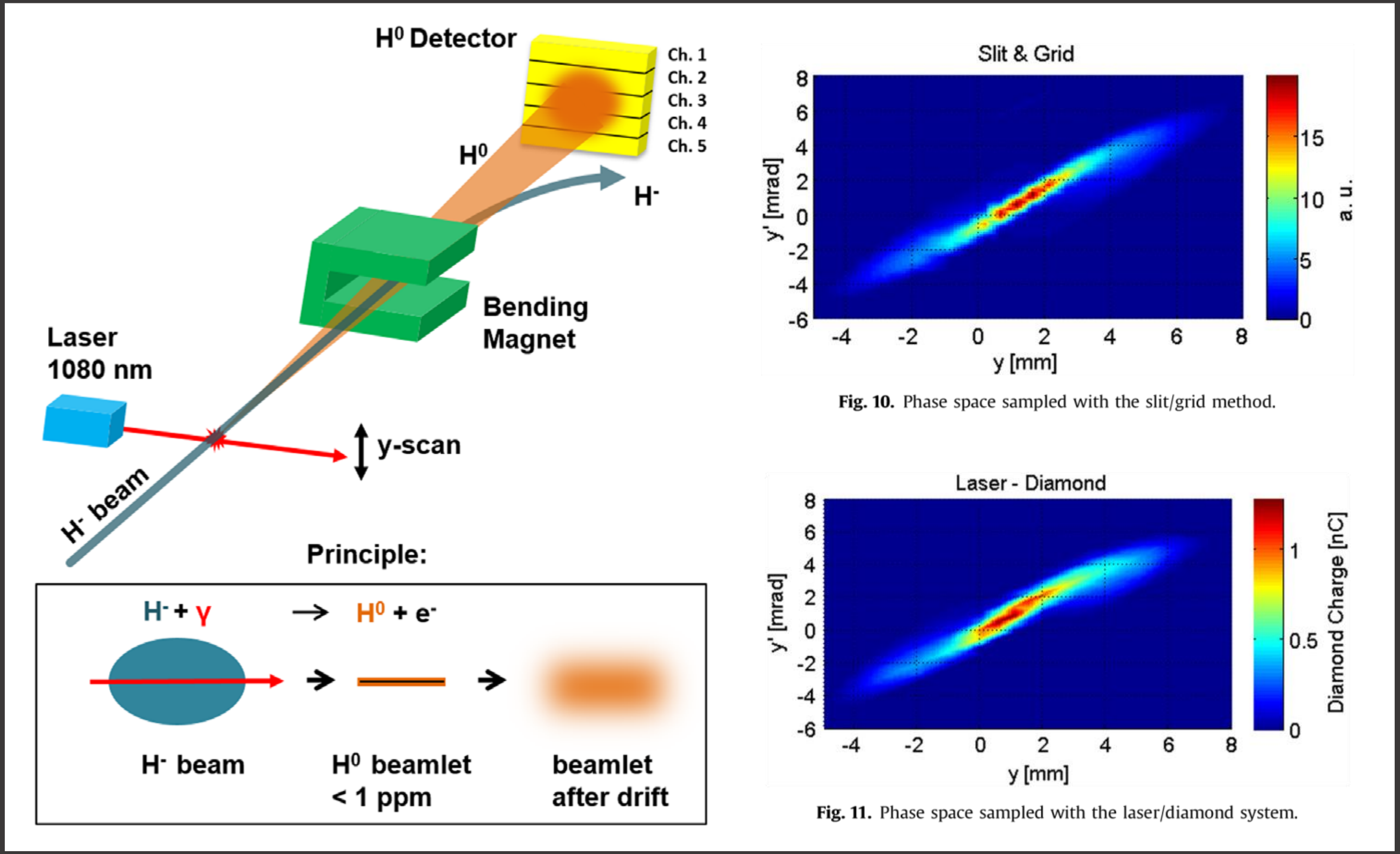

Fig. 10. Phase space sampled with the slit/grid method.

Fig. 11. Phase space sampled with the laser/diamond system.

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NIM A 903 (2018) 140-146 NIM A 830 (2016) 526–531 PRSTAB 18, 122801 (2015)

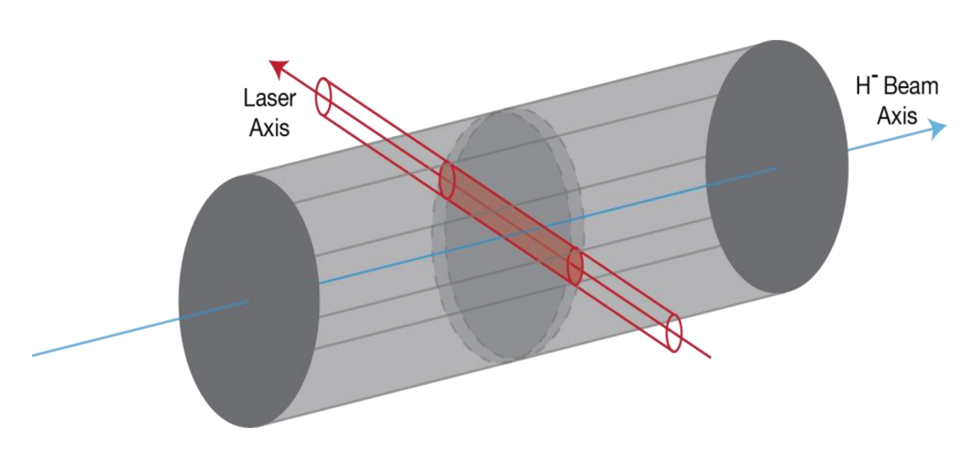
Laserwire

- A laserwire neutralises the hydrogen ion via the photodetachment effect, during which the secondary electron is ejected due to its low binding energy.

- The probability of interaction characterised by:

$$P_s = 1 - exp^{-\sigma(\lambda)\rho(x,y,z)t}$$

- Where σ(λ) is the cross section of interaction, ρ(x,y,z) is the photon density, and t is the time the ion spends in the ion beam.

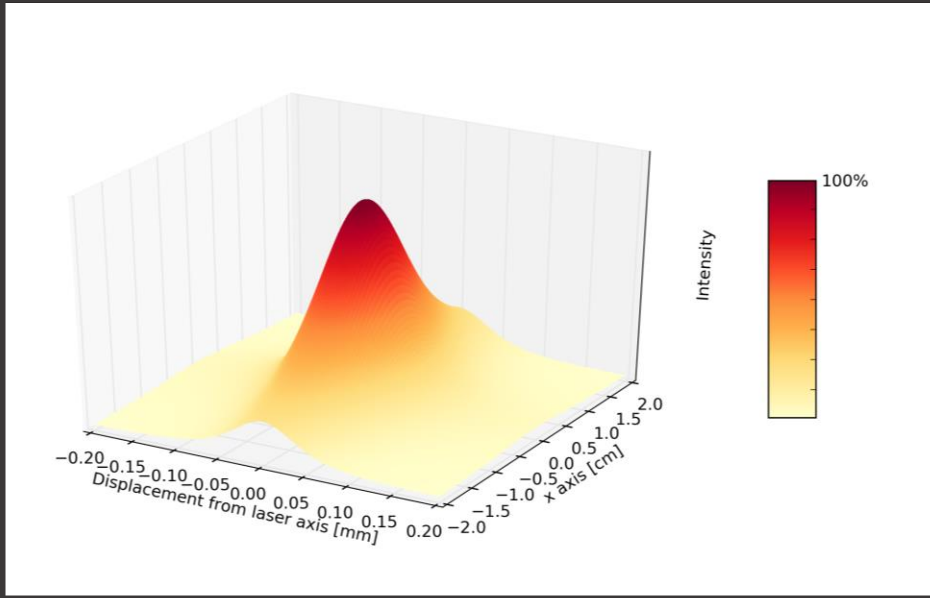


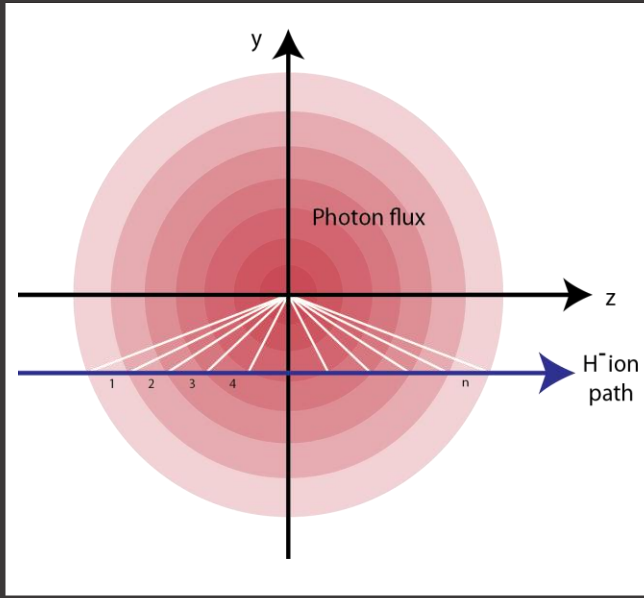
- Typically the laser is orthogonal to the ion beam trajectory.

- Changing the angle between the laser and the ion beam has an impact of the cross section due to the relativistic doppler effect.

Model Developments

- A new independent model was developed as a modular C++ package to simulate the interaction.
- The model took an input distribution and drifted each particle independently through a laser.
- The non-uniform photon density requires modification to the probability of stripping such that the ion path is discretized with the photon density evaluated at each step.





The probability then becomes:

$$P_s = 1 - exp^{-\sigma(\lambda)t\sum_{i=1}^{n}\rho(x_i,y_i,z_i)}$$

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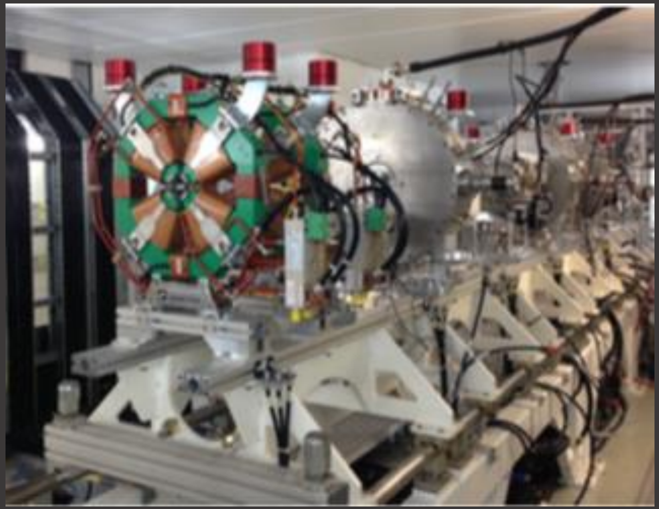
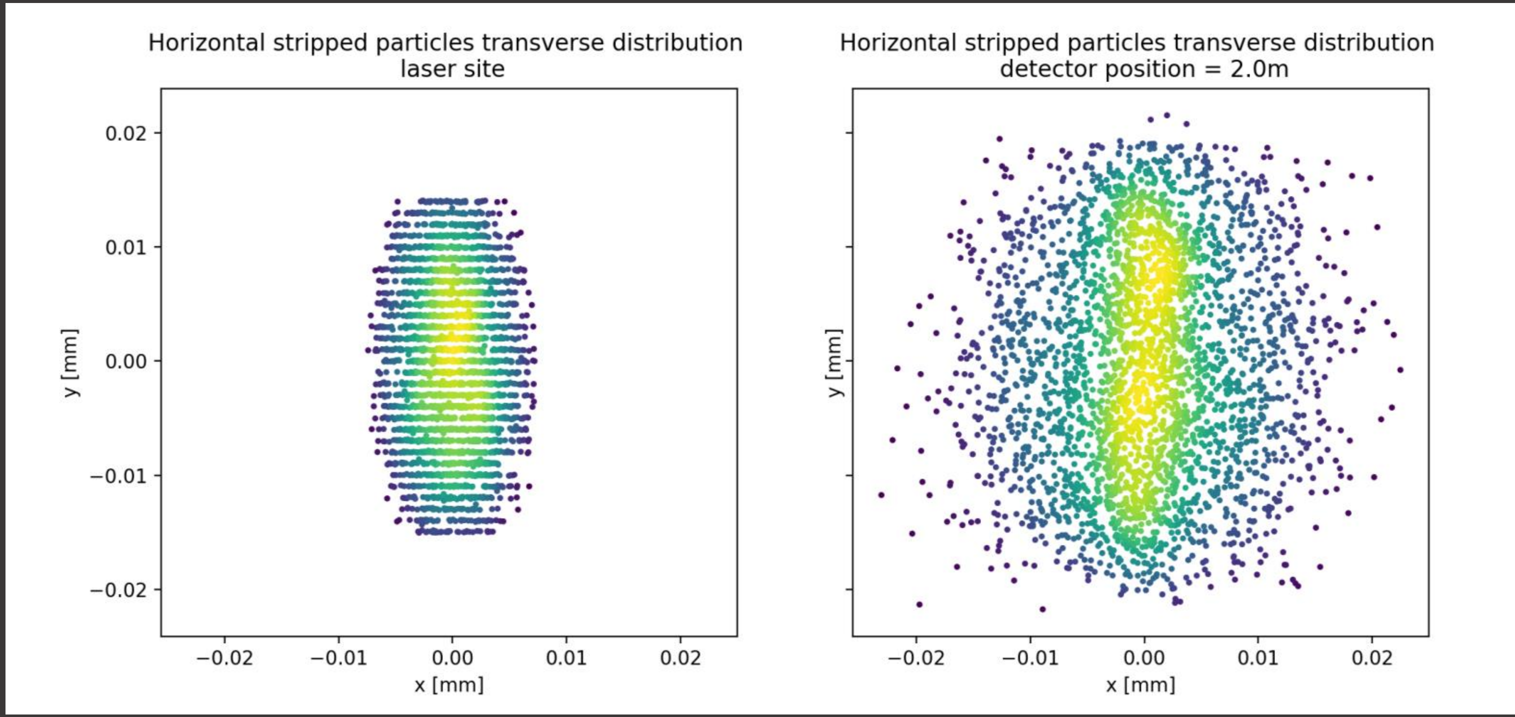
The Front End Test Stand - FETS

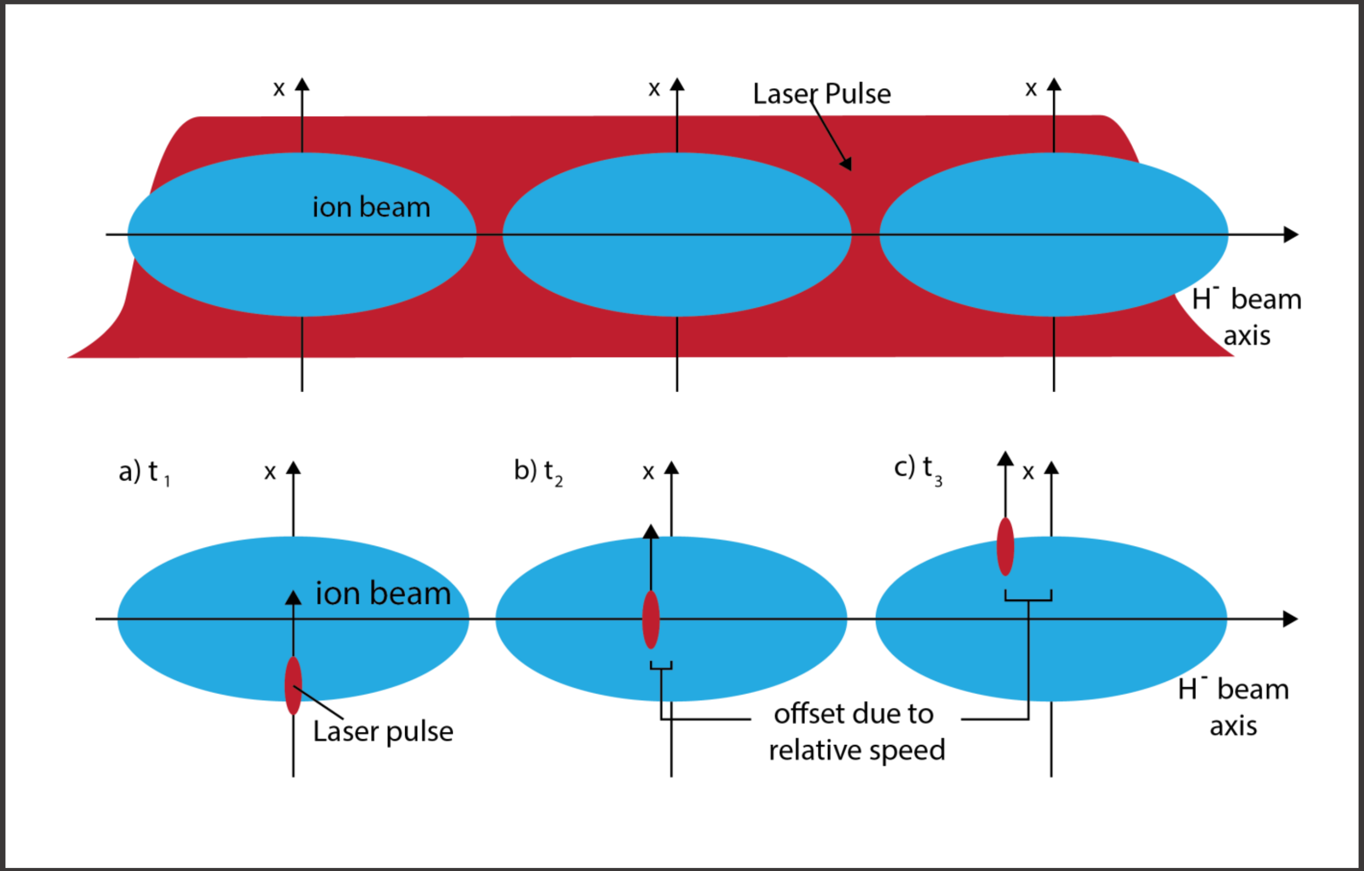
- Primarily a transverse laserwire model for FETS was developed and validated against the LINAC4 simulation.
- The model has been further developed for a novel longitudinal laserwire on FETS.





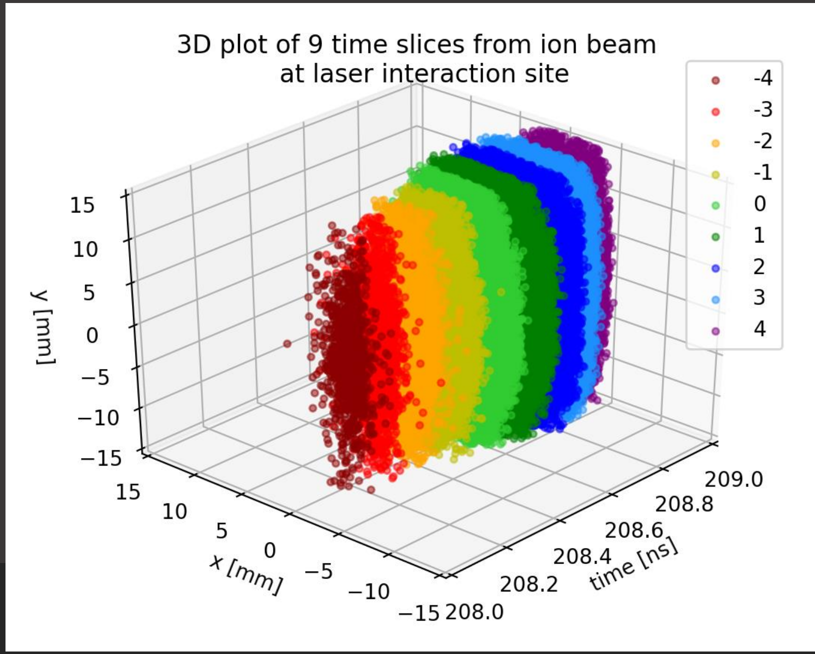
Beyond Transverse Profiling

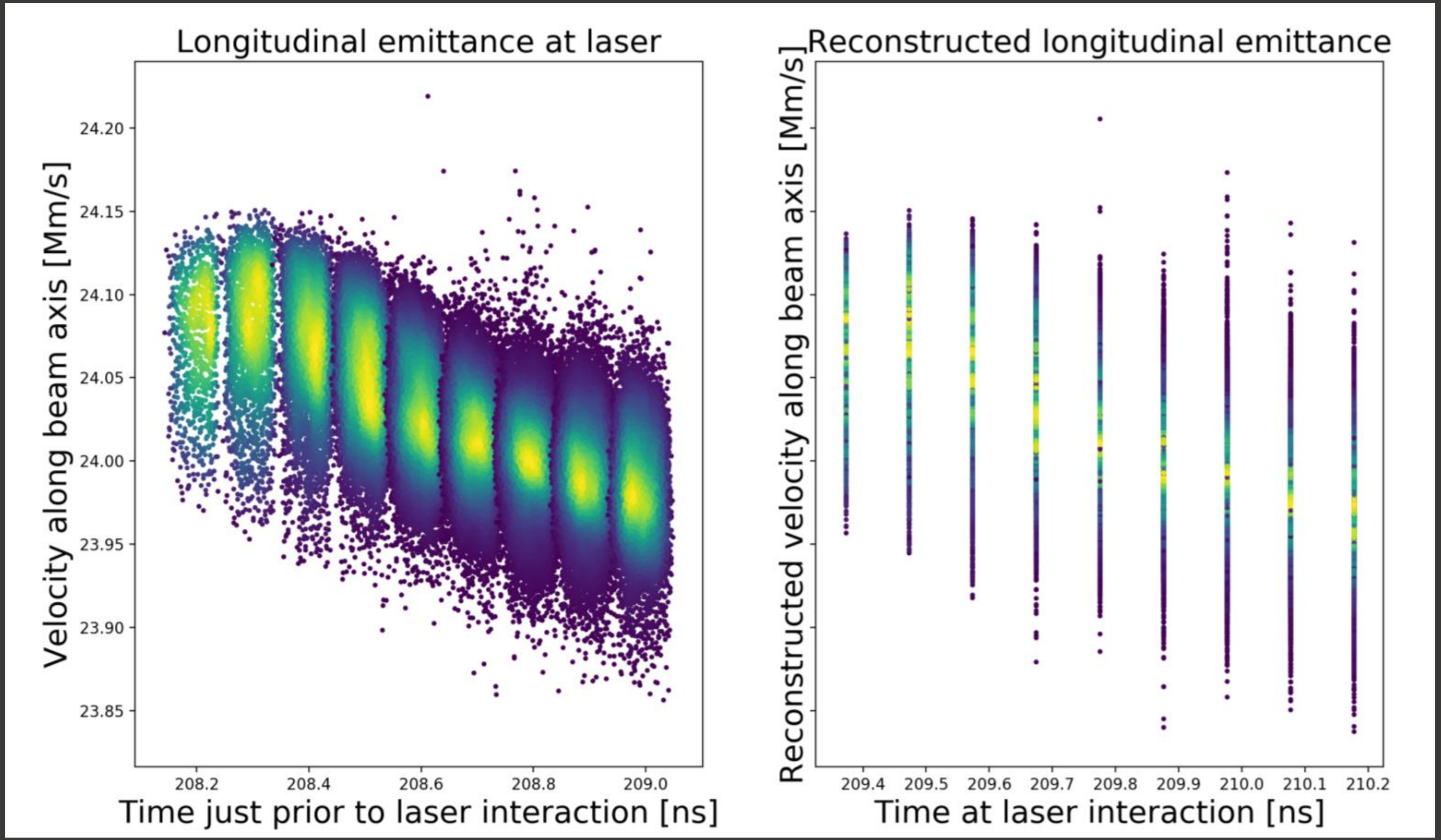
- The model was extended to allow for longitudinal beam profiling.
- For transverse measurements the laser pulse duration is longer than the ion bunch, sampling multiple bunches per pulse.
- For longitudinal measurements the laser pulse duration is reduced to less than the ion bunch.
- Due to the relative speeds of the two beams the resulting strip is no longer orthogonal to the ion beam trajectory.



Results from Longitudinal Sampling

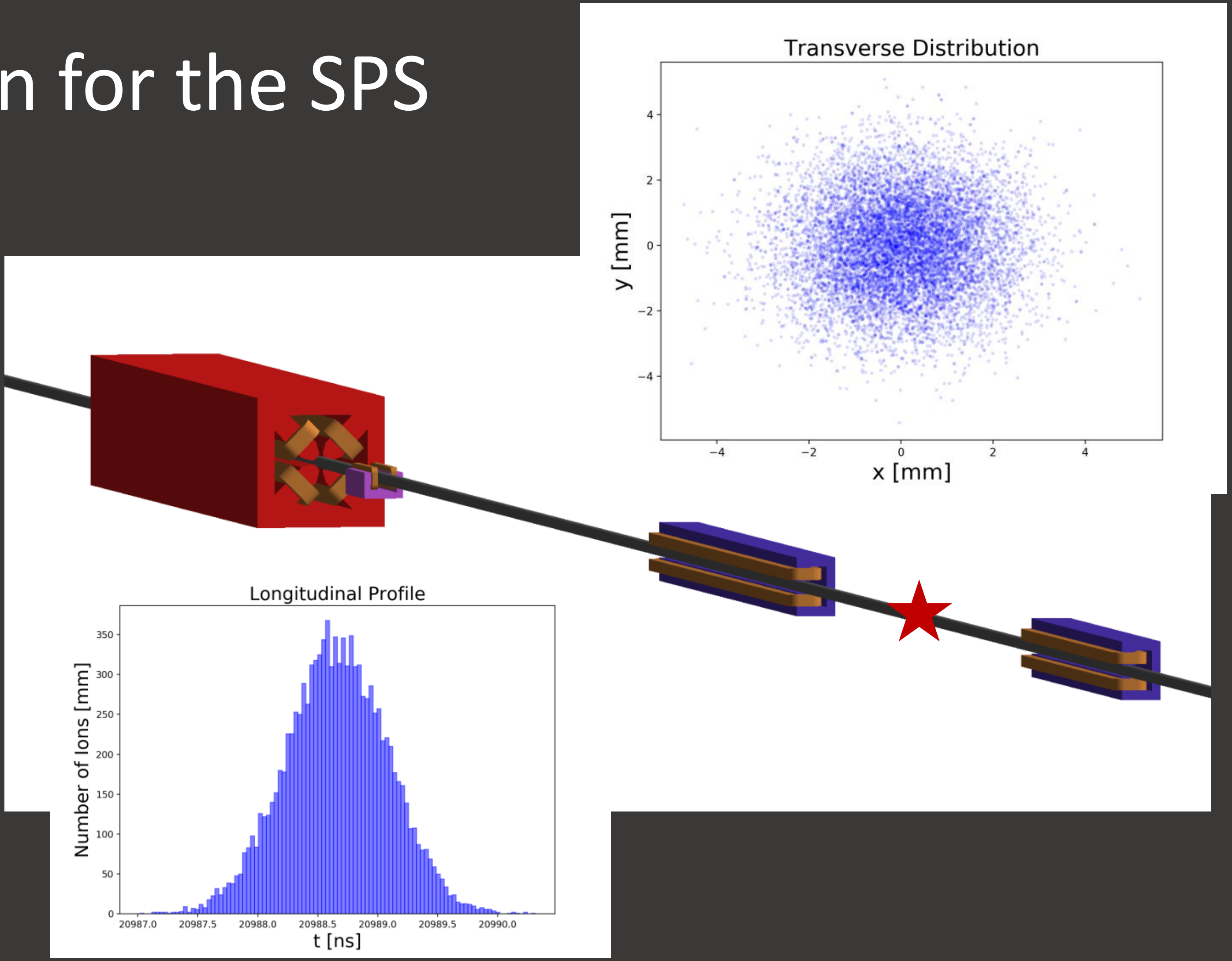
Synchronizing the laser with different positions within the beam allow multiple strips to be taken. This gives information about the time evolution of the beam and allows for the reconstruction of a longitudinal beam emittance.





Obtaining a Distribution for the SPS

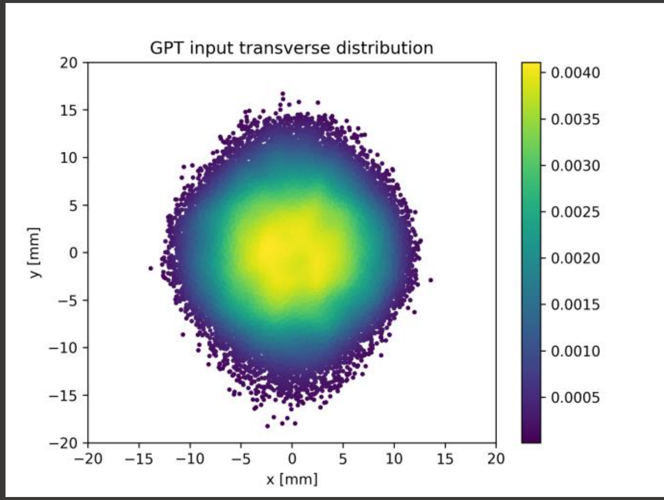
- Using a 2015 MADX input, the SPS was constructed for BDSIM.
- A 450GeV beam was then run through one turn of the model.
- The output distribution was selected as the drift from LSS6:616 between the kickers 61655 and 62676.
- The BDSIM output was converted for the laserwire model input including with the weight of a lead ion considered for the momentum. The time distribution was randomly generated with a Gaussian distribution.



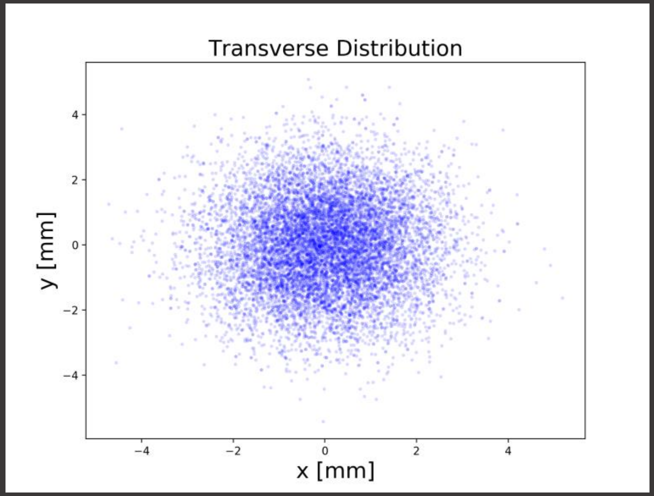
*"SPS GF PoP WG Scope, objectives, deadlines and status" B. Goddard

Parameter	FETS	GF Total σ_0	GF mean σ
Wavelength	1064nm	1034nm	1034nm
Cross Section	~3x10^-21 m^2	~4x10^-18 m^2	~6.989x10^-22 m^2
Pulse Duration	50 ps (FWHM)	250 ps (FWHM)	250 ps (FWHM)
Pulse Energy	1.0 µJ	1.0 µJ	5.1 mJ
M^2	1.8	1.6	1.6
Laser Waist (w0)	~100 µm	~4 mm	~4 mm
Angle of interaction	6°	6°	6°
Interaction length	3 cm	1 m	1 m
Scale	10	1	1
N particles in bunch	~1.16x10^9	~1.15x10^11	~1.15x10^11
N particles input	~1 mil	~110K	~110K
N interacted	321	25342	20571
% interacted	0.03%	23%	18.7%
Bunch Velocity	8%c	99%c	99%c

Input Distribution FETS



Input Distribution SPS



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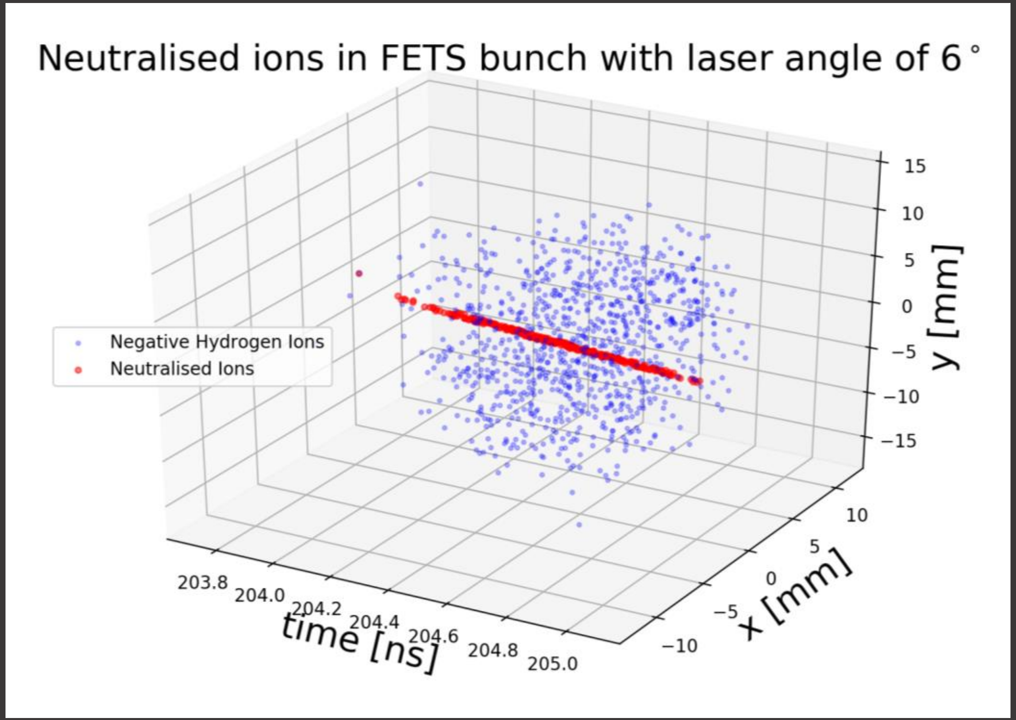
Results for FETS



- The proposed laser waist for the FETS accelerator is ~100µm with a maximum transverse beam width of ~3cm.
- The result is a small strip of neutralised particles approximately along the ion beam trajectory.
- The 6° angle offset from the beam axis validates the model functionality before running the SPS distribution.

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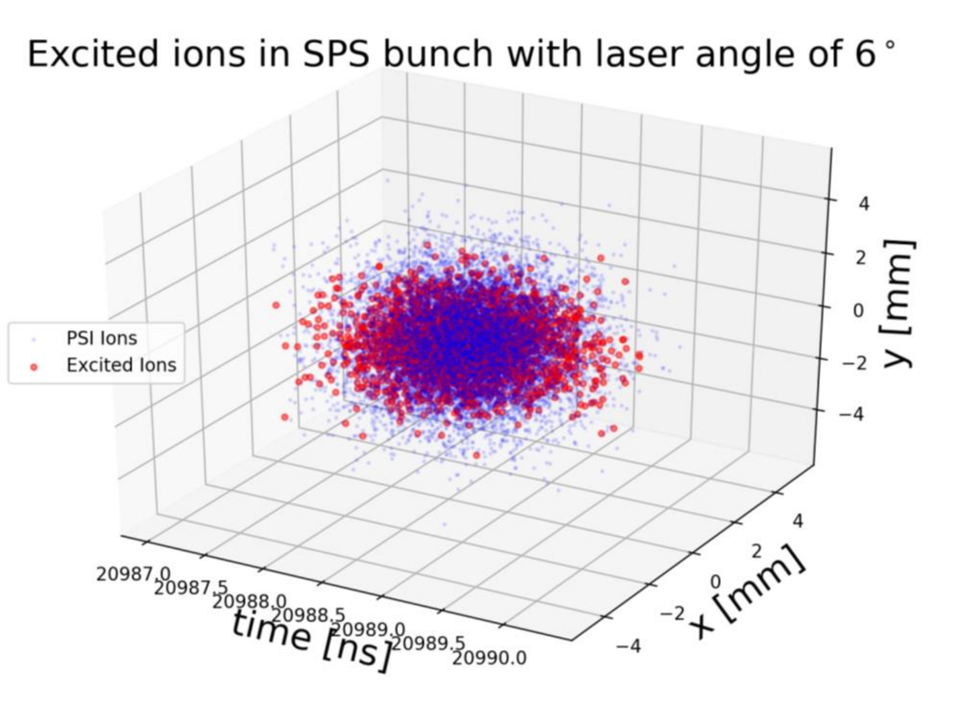
Results for SPS Distribution

- The proposed laser waist for the Gamma Factory is ~4mm with a maximum transverse beam width of ~1cm.
- The result is the interacting ions are spread across the entire bunch.
- Two cross sections were used – total cross section σ_0, and the mean cross section σ_m, at resonance. Resulting in 23% and 18% of the ions excited respectively.
- While there is a distribution in time of the excited ions, this is based upon the time the ions reach a user defined transverse plane – **not** the exact time the interaction occurred.
- This is due to the models construction of summing the probability of interaction across multiple steps.

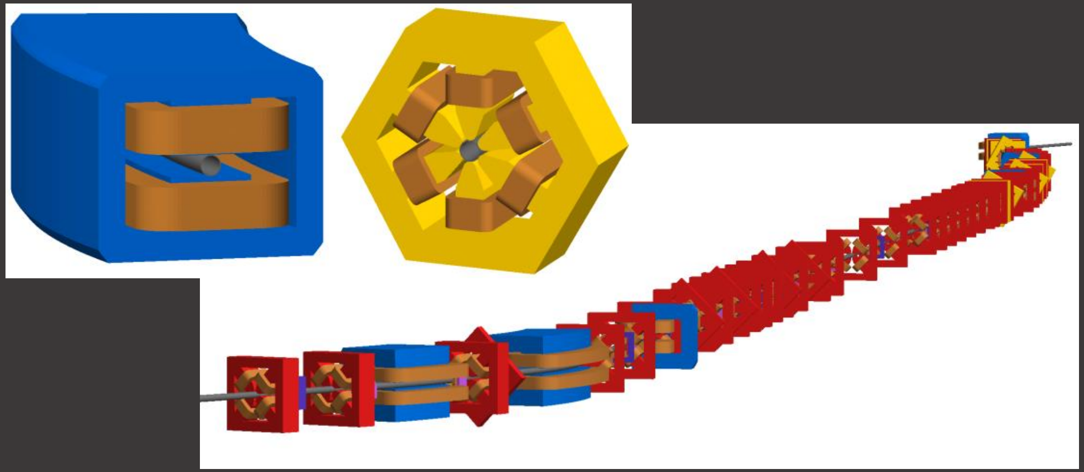


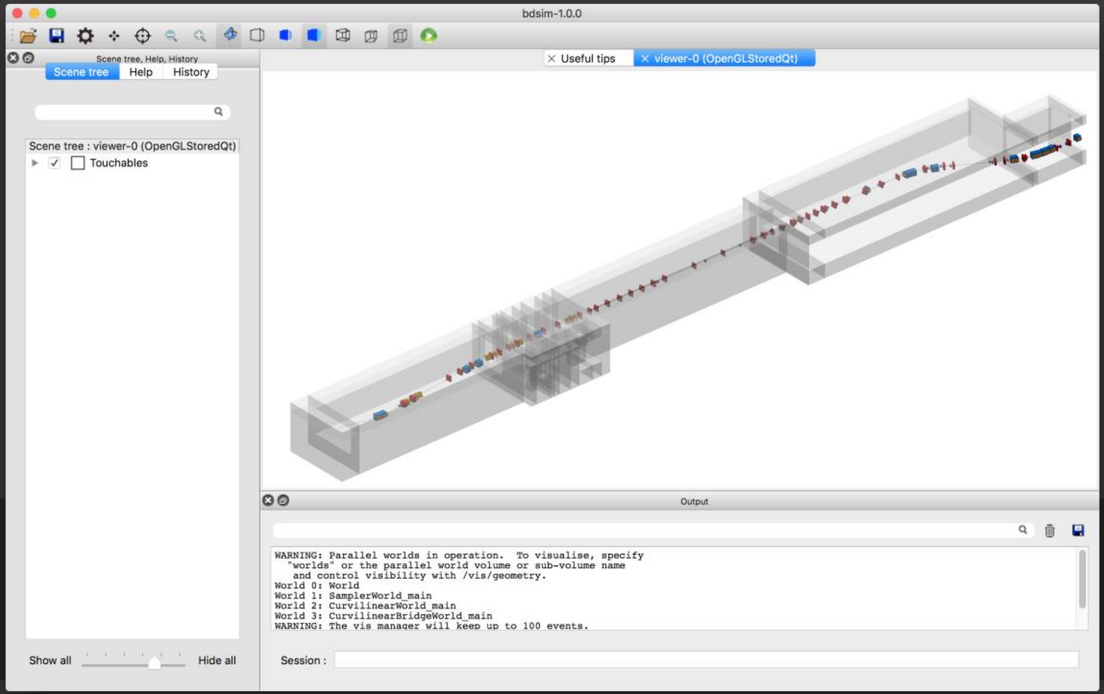
Motivation for including laser interactions in BDSIM

- The main motivation is to enable a simulation of the laser-ion beam interaction, including multi-turn particle tracking, a photon emission process with tracking to give energy deposition and distributions at potential detector positions, all in one software suite.

- BDSIM also inherently enables the exact time and location of the excitation to be simulated, which is not currently a feature of the stand alone C++ laserwire model that calculates a probability for interaction upon reaching a transverse plane.

Beam Delivery Simulation - Overview





- Create Geant4 model of an accelerator from optical description in minutes (uses CLHEP, ROOT and Geant4)
- Library of scalable generic accelerator geometry in Geant4 C++
- Can overlay other geometry and fields for more detail
- Thick lens 1st order matrices used for in-vacuum tracking, replaces Geant4's 4th order Runge-Kutta

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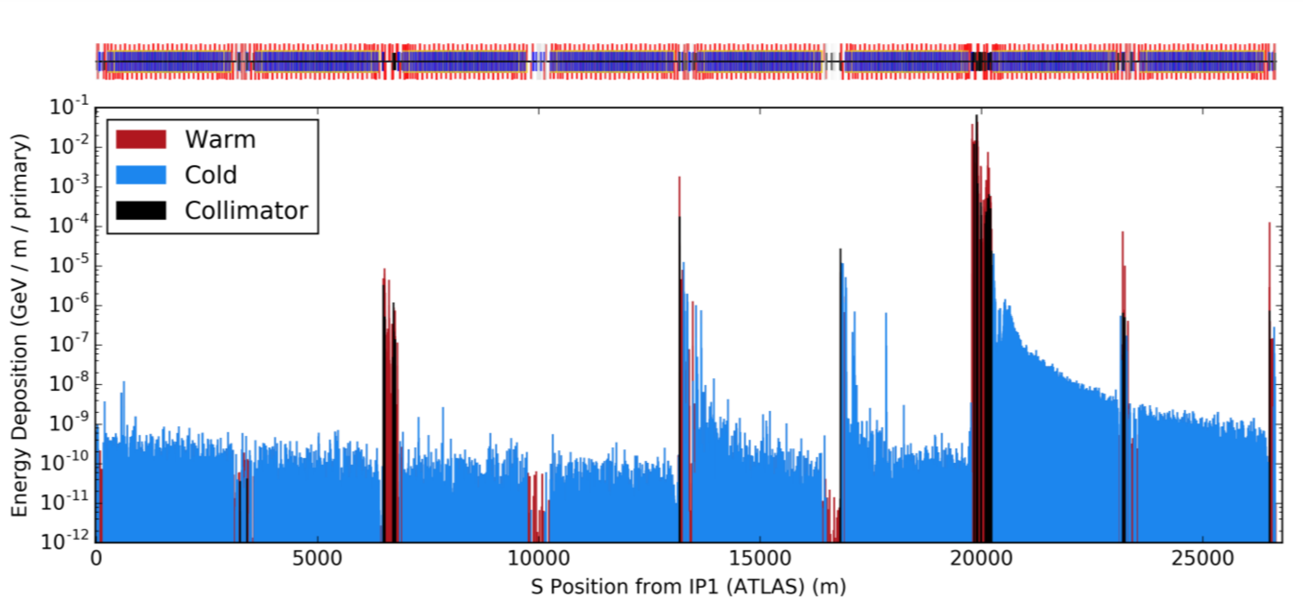
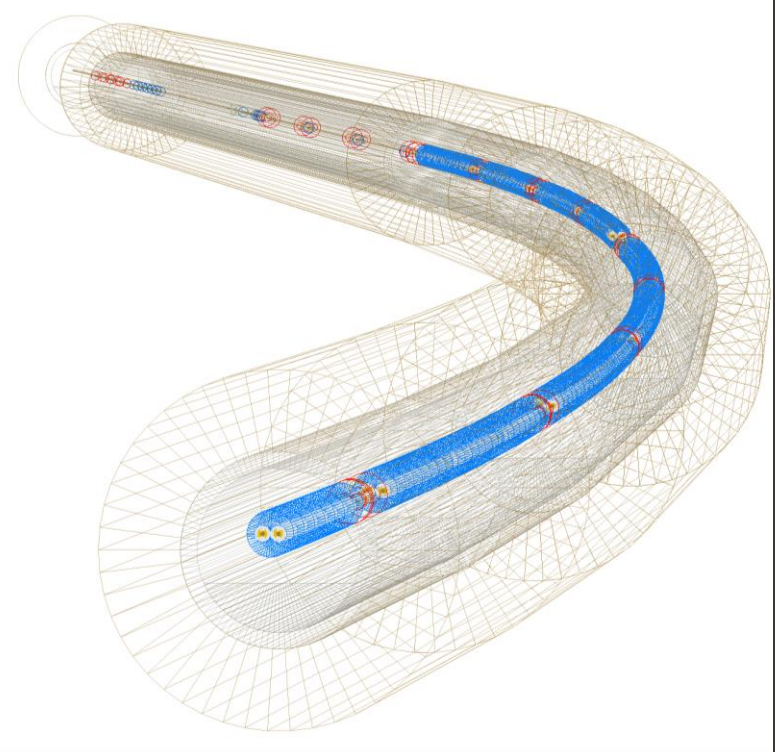
Beam Delivery Simulation - Functionality

- 27km LHC model with ~20k beam line elements
- Energy deposition for the full ring.





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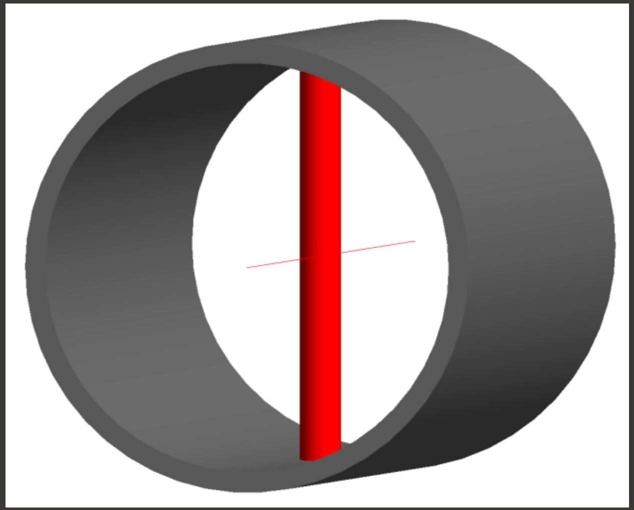
BDSIM Laser Implementation

- In BDSIM the laser will be modelled as a solid with a photon density based on Gaussian laser beam that can be modulated in time to represent a pulse.
- Pre-existing wire scanner geometry has been repurposed for initial implementation of the laserwire physics process.
- Future plans to have the laser geometry formed as a hyperbolic solid matching the Gaussian beam optics.
- The laser will exist in a parallel world such that it is not tied to one specific element in the beamline lattice.
- The physics processes for laser interactions are not included in GEANT4 but has been added to BDSIM and currently under testing.
- There is a challenge in accounting for excited states for continued tracking and the eventual photon emissions.



Including Photon Emission

- Plans for developing the photon emissions are to make use of existing GEANT4 decay mechanisms.
- Existing mechanisms are for nuclide decays – which will be modified to specify a custom decay product, which will be assigned an energy, half life of decay and Lorentz boost by Geant4.
- Once the gammas have been produced, BDSIM tracks each one individually with all the correct physics processes through the lattice.
- Furthermore the beam could be cycled through the SPS lattice for multiple turns including the laser interaction on every turn and recording the produced gamma distribution for each turn.

Summary and Discussion

- A laser-ion interaction model has been developed originally for installation of laserwires at various facilities.

- The simulation of the laser interaction with lead ions in the SPS found a excitation of ~23% sampled ions. This was for a laser pulse energy of 1.0µJ and duration of 250ps.

- This model of laser-ion interactions has been added to BDSIM – currently the geometry is functioning, the physics process for excitation has been added and is under testing.

- The extension to include the photon emissions has been examined and details of how it will be implemented discussed.

- Once all processes are operational the full distribution of resulting photons and their energy deposition will be modelled over multiple turns through the SPS.

Thank you for listening!