BDSIM Applications and Further Industry Connections

Laurie Nevay, RHUL

on behalf of the JAI

JAI Advisory Board - 7th April 2022

Introduction

- The JAI has fundamental science at its heart, but promoting advanced accelerator applications in science and society is part of the mission
- Connection with industry is a natural and valued part of its activity
- An overview of other recent industry connections is presented here:

1. eSYLOS LWPA at ELI-ALPS
2. Industrialisation of BPMs for FELs
3. Pyroelectric accelerator facility
4. BDSIM applications

- JAI industrial activity is supported by technology transfer experts that reside in each institution
- They guide or manage aspects of IP/contracts/fundraising etc to enable the pathway to commercialisation and support JAI researchers to make strategic decisions on commercialisation of the technology

eSYLOS - LWFA beamline at ELI-ALPS

Z. Najmudin, G. Hicks, R. Kumar-Yembadi

- JAI development of LWFA beamline at ELI-ALPS using the SYLOS laser
- The Extreme Light Infrastructure project started as a bottom-up initiative by the European scientific laser community and the network of large national laser facilities, LASERLAB-EUROPE
- The facilities were built in parallel in the Czech, Hungary and Romania, starting 2011 and completed in 2018 funded by European Regional Development Funds (ERDF) and contributions from the host countries totalling about 850 million euros.
- The main objective of ELI Attosecond Light Pulse Source (***ELI-ALPS***) is the establishment of a unique attosecond facility which provides ultrashort light pulses between THz (10^{12} Hz) and X-ray (10^{18}-10^{19} Hz) frequency range with high repetition rate for developers and end-users.

SYLOS Laser

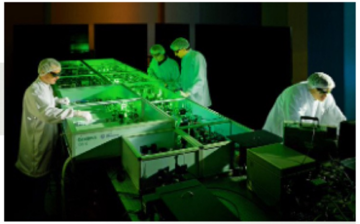
Z. Najmudin, G. Hicks, R. Kumar-Yembadi

- ELI generally built on commercially available (but cutting-edge) technology.
- SYLOS laser built by EKSPLA in Lithuania will deliver > 100 mJ in < 10 fs at 1 kHz
- This enables the scaling of laser wakefield accelerators to higher density
  - for extremely compact high repetition rate sub-femtosecond electron beams
- JAI-Imperial funded (via competitive tender) to £855k to implement ultrafast electron beamline using SYLOS laser = ***eSYLOS***

UltraFlux Custom

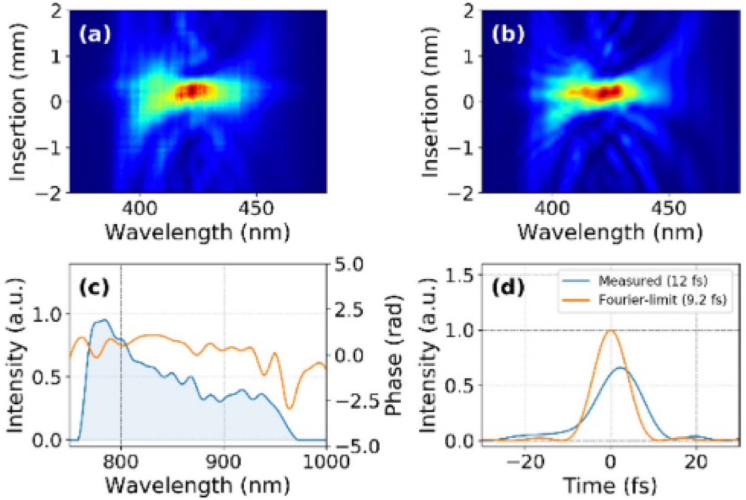
Multi TW Few cycle OPCPA systems

/ > 15 TW peak power
/ sub-8 fs pulse duration
/ 1 kHz repetition rate
/ > 120 mJ output energy
/ > 120 W average power



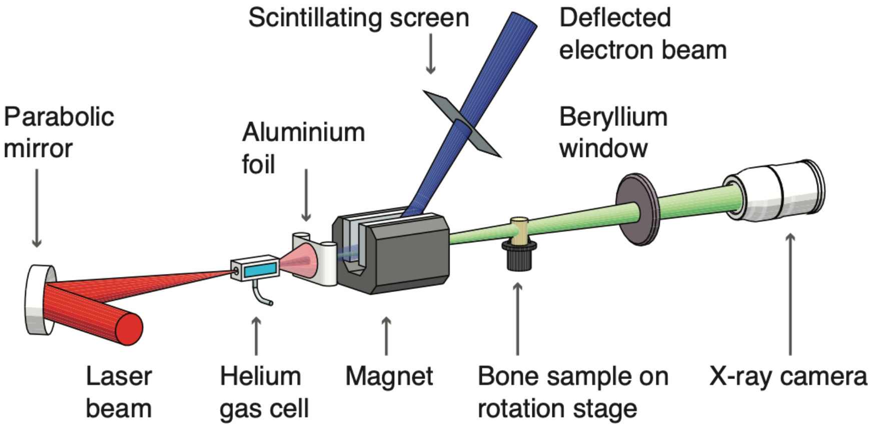
EKSPLA

Download datasheet PDF

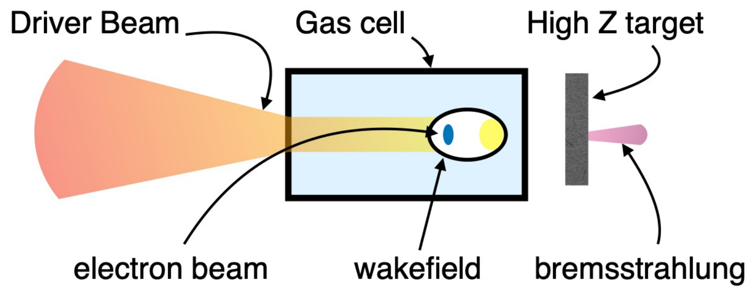


eSYLOS Radiation Techniques

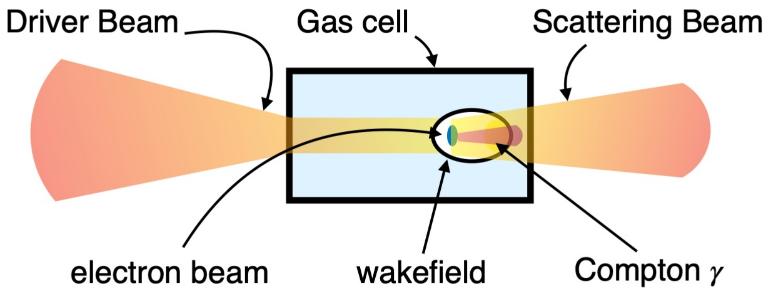
Z. Najmudin, G. Hicks, R. Kumar-Yembadi



Betatron emission from low energy source emission ~keV



Bremsstrahlung emission from solid target ≳MeV



Compton Scattering from low energy probe ≳keV

John Adams Institute for Accelerator Science

eSYLOS Parameters For Reference

eSYLOS Radiation Summary

Property	Symbol	Expression	Calculated
Laser Energy	E_L		50 mJ
Pulse duration	τ_L		10 fs
Peak Laser Power	P_L	E_L/τ_L	5 TW
Rep rate	N_{rep}		1000 Hz
Laser Wavelength	λ_0		0.8 µm
Critical Density	n_{cr}	$\epsilon_0 m_e \omega_0{}^2/e^2$	1.74×10^{27} m^{-3}
Design a_0 [1]			2.0
Intensity	I_L	$I_{18} = (1.17 \times a_0)^2/\lambda_{\mu m}{}^2$	8.55×10^{18} Wcm^{-2}
Spot size [2]	w_0	$(1/\pi)(P_L/I_L)$	2.4 µm
Relativistic wave	λ_p	$2\pi c/\omega_p = w_0$	2.4 µm
critical density over density	n_{cr}/n_e	w_0/λ_0	9.25
electron density	$n_{cr}/(n_{cr}/n_e)$	n_e	1.88×10^{20} cm^{-3}
Maximum Energy	W_{max}	$2(n_{cr}/n_e) m_e c^2$	9.45
Lorentz factor	γ_0	$W_{max}/m_e c^2$	18.5
Dephasing Length	L_{deph}	$(n_{cr}/n_e)^{3/2}\lambda_0$	180 µm
Skin depth	$\ell_{sd} = c/\omega_p$	$\lambda_0/2\pi(n_{cr}/n_e) = w_0/2\pi$	0.39 µm
Charge	q	$\frac{4}{3}\ell_{sd}{}^3 n_e$	$9.2 \times 10^7 = 14.7$ pC

Betatron Radiation

Property	Symbol	Expression	Calculated
Betatron wavelength	λ_β	$\sqrt{2\gamma_0}\ \lambda_p$	14.8 µm
Undulator radiation	λ_{urad}	$\lambda_\beta/2\gamma_0{}^2$	21.6 nm
Undulator parameter	a_β or K	a_0 [3]	2.0
Critical wavelength	λ_{crit}	λ_β/a_β	10.8 nm
Critical Energy	E_{crit}	hc/λ_{crit}	114 eV
Betatron periods	N_β	L_{deph}/λ_β	12.2
Energy per electron	E_{rade}	$\frac{e^2}{12\pi\epsilon_0}\gamma_0{}^2 a_\beta{}^2 k_\beta{}^2 L_{deph}$	3.4×10^{-18} J
Total Energy Radiated	E_{rad}	qE_{rade}	3.14×10^{-10} J
Number of photons	N_{phot}	E_{rad}/E_{crit}	1.7×10^7
Divergence	θ_β	a_β/γ_0	0.11 rad = 6.2°
Radiation size	r_β	$a_0 c/(\gamma_0\omega_\beta)$	0.26 µm
Radiation length	τ_β	ℓ_{sd}/c	1.3 fs
Peak Brightness [4]	B_{peak}	$(N_{phot}/1000)/\theta_\beta{}^2\pi r_\beta{}^2\tau_\beta$	1.6×10^{21} [5]
Average Brightness	B_{av}	$N_{rep} * (N_{phot}/1000)/\theta_\beta{}^2\pi r_\beta{}^2$	7.1×10^9 [5]

Thomson Scattering

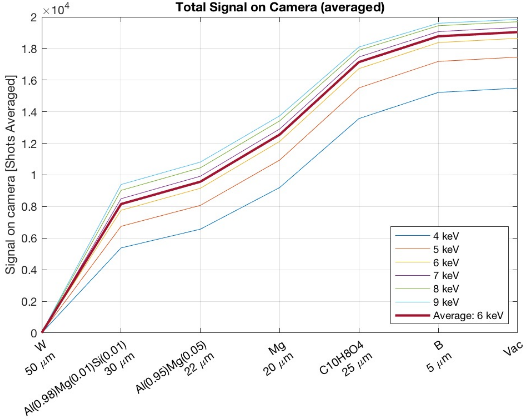
Property	Symbol	Expression	Calculated
Thomson wavelength	λ_{comp}	$\lambda_0/2\gamma_0{}^2$	1.2 nm
Upscattered energy	E_T	hc/λ_{comp}	1.1 keV
Thomson cross-section	σ_T	$\frac{8}{3}\pi r_e{}^2$	6.65×10^{-29} m^2
Probe energy	E_{pr}		1 mJ
Probe photons	N_{pr}	$E_{pr}/(hc/\lambda_0)$	4.0×10^{15}
Scattered photons [6]	N_{sc}	$N_{pr}\sigma_T n_e c\tau_\beta$	1.9×10^7
Divergence	θ_T	$1/\gamma_0$	0.054 rad = 3.1°
Duration	τ_L	τ_L	10 fs
Radiating size	r_β	$a_0 c/(\gamma_0\omega_\beta)$	0.26 µm
Peak Brightness	B_{Tpeak}	$(N_{phot}/1000)/\theta_T{}^2\pi r_\beta{}^2\tau_L$	3.14×10^{21} [5]
Average Brightness	B_{Tav}	$N_{rep} * (N_{phot}/1000)/\theta_\beta{}^2\pi r_\beta{}^2$	3.1×10^{10} [5]

Bremsstrahlung

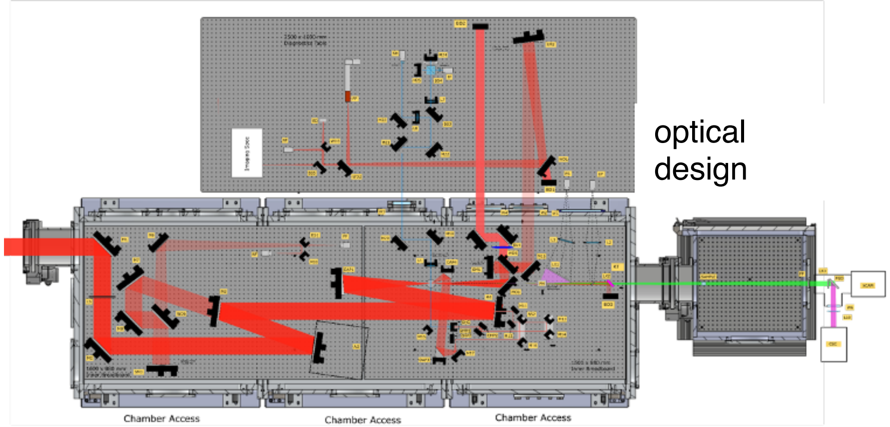
Property	Symbol	Expression	Calculated
Bremsstrahlung min wavelength	λ_{min}	$hc/\gamma_0 mc^2$	0.13 nm
Upscattered energy	E_{max}	hc/λ_{comp}	9.45 MeV
Bremsstrahlung peak wavelength	λ_{brem}	$\approx 2\lambda_{min}$	0.26 nm
Peak Bremsstrahlung energy	E_{max}	hc/λ_{brem}	4.72 MeV
Bremsstrahlung cross-section	σ_B	tabulated	1×10^{-22} m^2
Bremsstrahlung photons [7]	N_{Bph}	$\approx N_e$	9×10^7
Divergence	θ_B	$1/\gamma_0$	0.054 rad = 3.1°
Duration	τ_B	τ_β	1.3 fs
Radiating size	r_B		100 µm [8]
Peak Brightness	B_{Bpeak}	$(N_{phot}/1000)/\theta_T{}^2\pi r_\beta{}^2\tau_L$	7.6×10^{17} [5]
Average Brightness	B_{Bav}	$N_{rep} * (N_{phot}/1000)/\theta_\beta{}^2\pi r_\beta{}^2$	9.8×10^5 [5]

eSYLOS Status

- TDR completed
- Extra chamber for sample irradiation
- Engineering for end of April 2022
- Construction and commissioning to continue throughout 2022
- Operation due early 2023

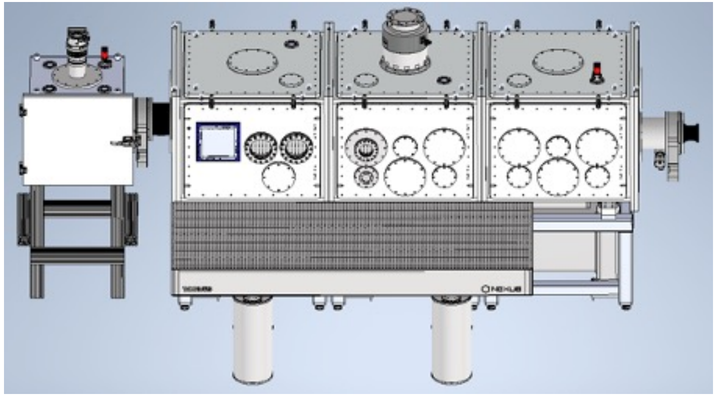


target and filter pack simulations



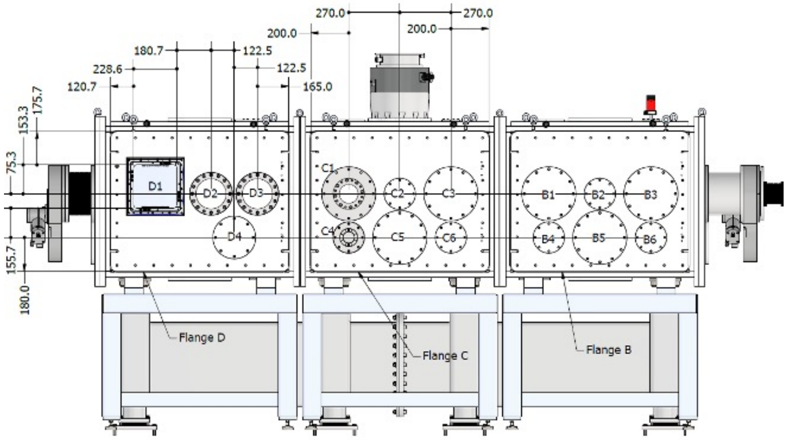
optical design

engineering design

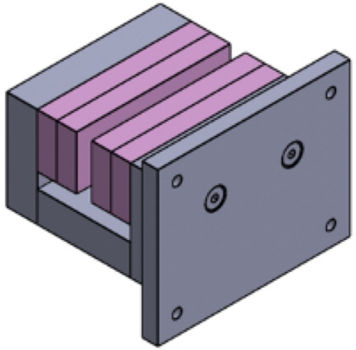


eSYLOS Industrial Connections

- Unique requirements have required constant contact with suppliers
- Custom vacuum design - Egken, Poland
- Breadboard isolation - Quantum Optics Group, ICL
  - developed by Prof. John Tisch in Q.O.G.: purchased through Imperial College Consultant Management (ICON)



Compact magnet designs - Magnet Sales (UK)



High reflectivity and low GDD IBS mirrors - Manx Precision Optics (UK)

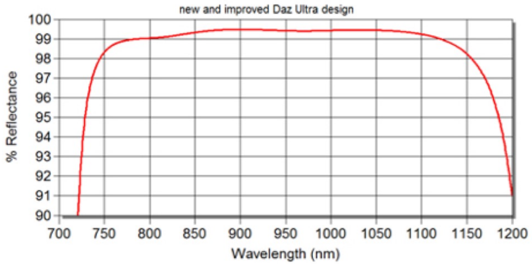
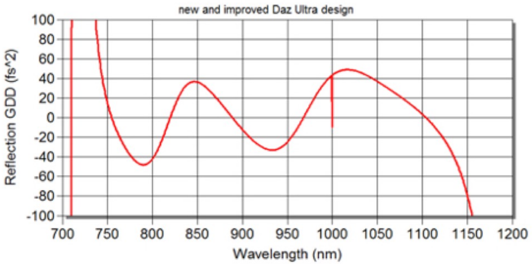


Figure 26: Reflectance Curve for custom Hybrid Metal-Dielectric Optic.



Update on Industrialisation of BPMs for FELs

John Adams Institute for Accelerator Science

A. Lyapin

- Recap:
  - cavity BPMs design for FELS, original developed for linear colliders
  - Offer complete off-the-shelf system in partnership with FMB-Oxford and iTech
  - first delivery to ELI-BL in 2021
  - REF2021 case study
- Current:
  - recovering and upgrading the test system at Daresbury post-Covid
  - install the second down-converter stage for low charge running
  - sadly, no beam for resolution studies expected for 18-24 months
  - but: trial of < 10pC running April 7th - 8th
- Spin-off project:
  - precision compact RF sources in development
  - aiming to present a prototype at IBIC22

CBPM triplet at CLARA, Daresbury Laboratory

New electronics: second down-conversion stage

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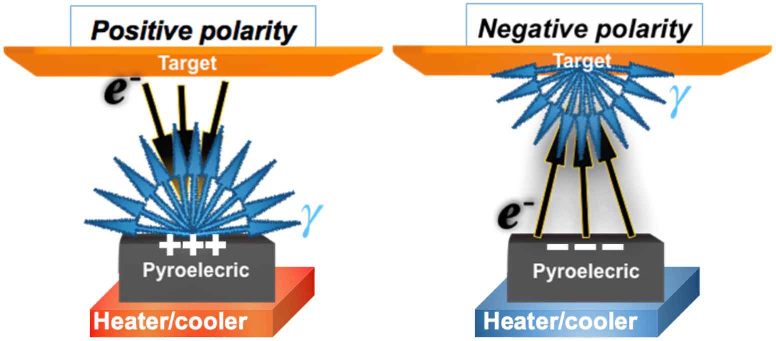
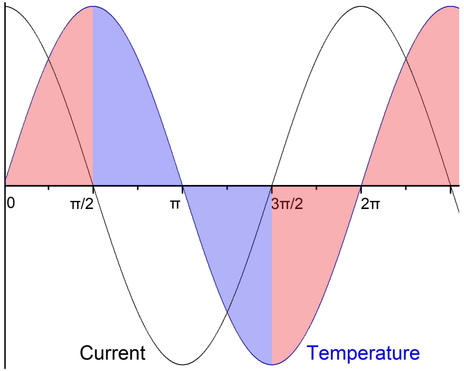
Pyroelectric Accelerator X-Ray Source

P. Karataev, A. Oleynik (Phd 2022), M. Ali (new Phd)

- Goal: develop a miniature source of X-rays without the need for high power / high voltage or radioactive sources
- Suitable for difficult-to-reach or clean places:
  - e.g. space station, mountains, underground mines
- However, instabilities within the accelerator need to be understood
  - related to the temperature change regime, target and crystal configuration and purity, vacuum level and accelerator geometry
- Develop a compact inexpensive particle beam facility at RHUL for educational and practical purposes
- Find a way to create impact by commercialising the technology

SCHEME OF GENERATION OF ELECTRONS AND X-RAYS AT PYROELECTRIC EFFECT



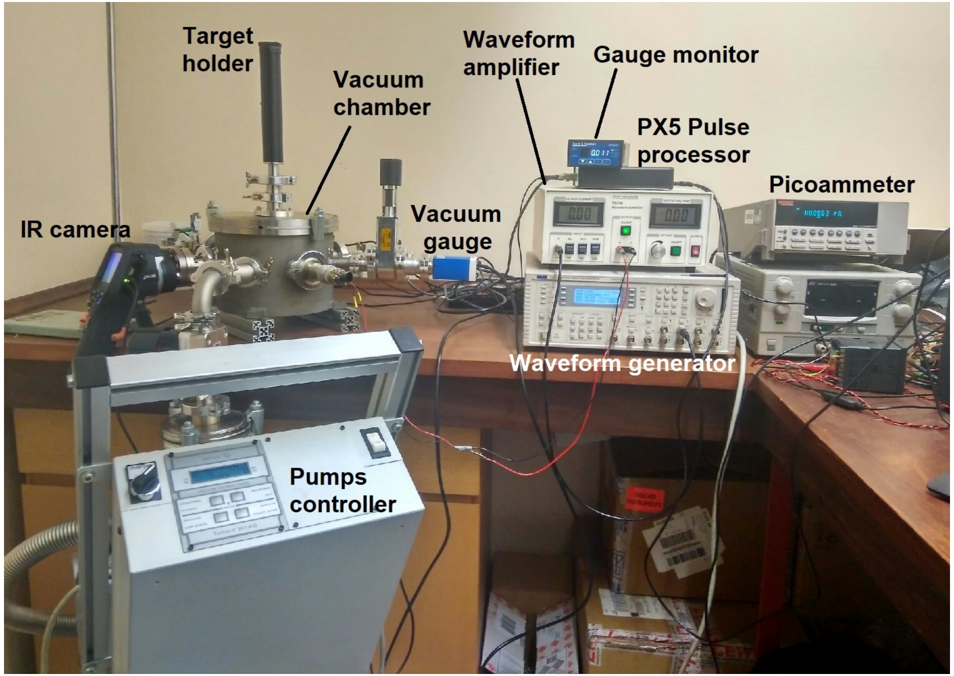


A Pyroelectric Accelerator Facility at RHUL

John Adams Institute for Accelerator Science

P. Karataev, A. Oleynik, M. Ali

- Achieved so far:
  - the facility has been created
  - a series of experiments on generation of electrons and X-rays have been performed
  - stabilization of emission has been achieved
  - Energy Dispersive Analysis of two target samples have been demonstrated
- Current Status:
  - one PhD student has completed and another PhD student has taken over the research
  - continue investigation of stability issues changing the accelerator conditions (vacuum, target to crystal distance, frequency and amplitude of temperature oscillations)
  - novel generation schemes are being considered for higher efficiency and higher energy X-ray production



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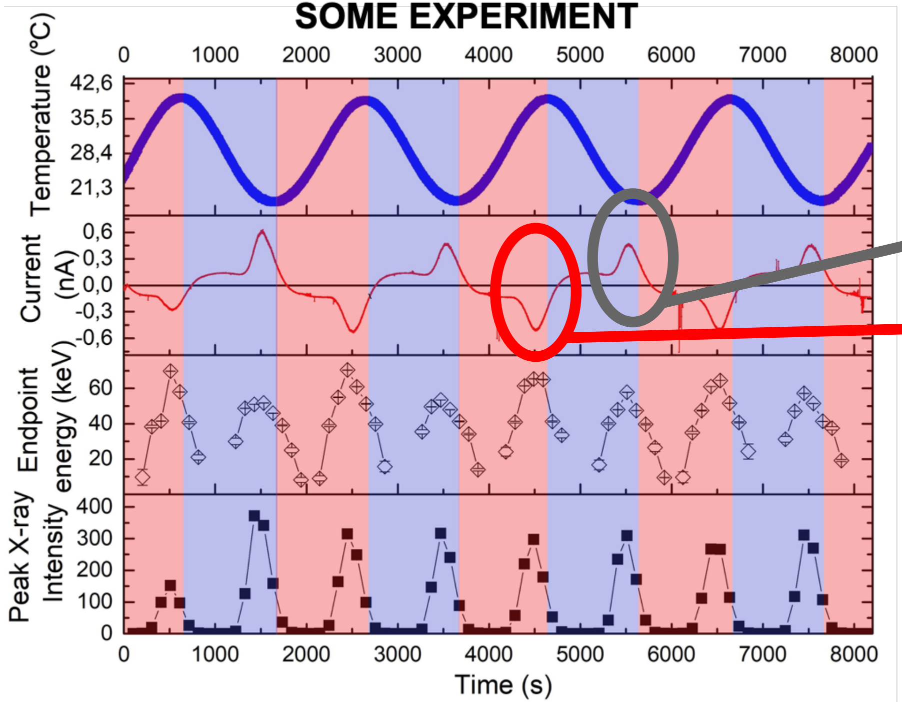
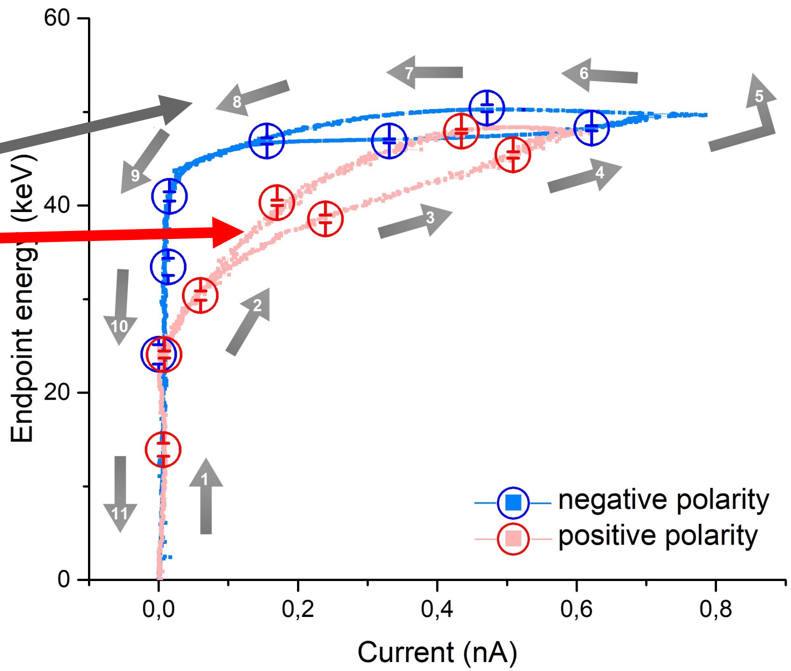
Results

P. Karataev, A. Oleynik, M. Ali

THE MEASURED PARAMETERS DURING SOME EXPERIMENT



Hysteresis loop of the avalanche process
For positive and negative polarity



Radiation Transport Simulations

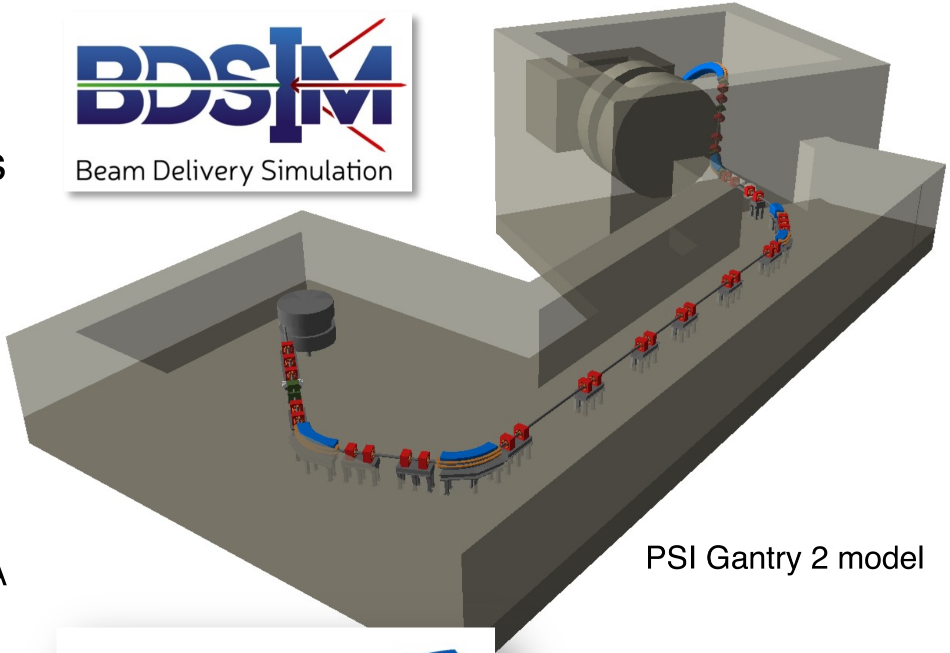
L. Nevay, S. Boogert, W. Shields, S. Alden

- Specialism in simulation developed since 2004
  - dedicated projects and effort since 2013
- Original research was on muon backgrounds for linear colliders
  - need both accelerator tracking and particle-matter interaction
- Key software created:
  - BDSIM program for 3D radiation transport models of accelerators
    - private variant including laserwire (Compton + photo-detachment; transverse + longitudinal)
  - pyg4ometry for RT geometry preparation, conversion, validation, comparison
- L. Nevay and S. Boogert and now part of the Geant4 collaboration
  - advanced geometry visualisation, crystal channelling physics

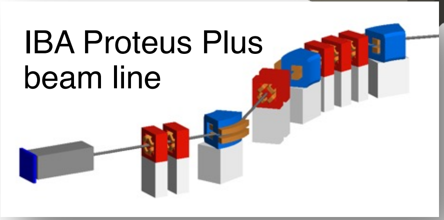
BDSIM

L. Nevay, W. Shields, S. Boogert

- BDSIM re-developed since 2013
- Automatic Geant4 models of accelerators
- Applied to many experiments and machines
  - ***ILC / CLIC**, **AWAKE, XFEL** undulators, **LHC** collimation, **Laserwires, ATLAS** non-collision backgrounds, **MAGIX** at **MESA**, and recently **FASER, FPF, FCC-ee, KLEVER, NA62 (PBC)***
- Also strong application for **medical therapy systems**
  - including radiobiological research facilities - e.g. LhARA
- Est. 50-100 users worldwide
- Enables vastly reduced time to create Geant4 models of accelerators



PSI Gantry 2 model

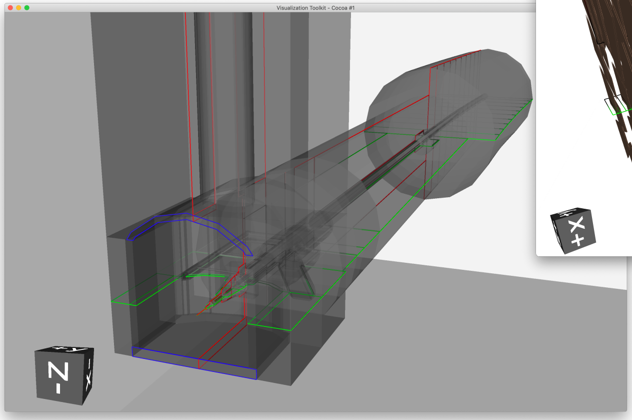


Manual users 2021-2022
7-day users: 65
14-day users: 101
28-day users: 199

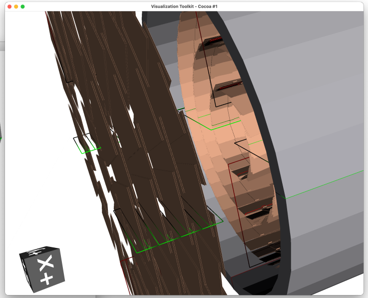
[Computer Physics Communications (252), July 2020, 107200]

Associated Capability

- **pyg4ometry**
- create, visualise, validate, modify, convert, composite geometry
- Geant4, FLUKA, ROOT, STEP
- Applications as broad as Geant4 & FLUKA



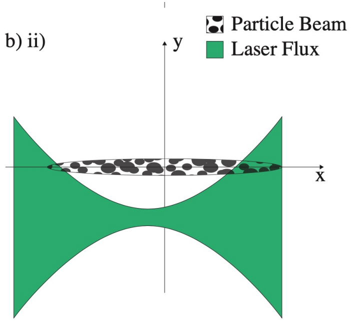
LHC model composition

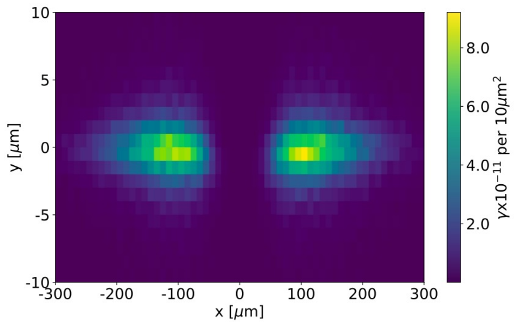


Silicon detector

Computer Physics Communications, 272 March 2022, 108288

- **Laserwire** simulation in BDSIM
- Introduction of laser volumes in Geant4 + new physics processes
- Compton-scattering and H^- photo-detachment
- From saturation to 'passive' LWs
- Full overlap integral





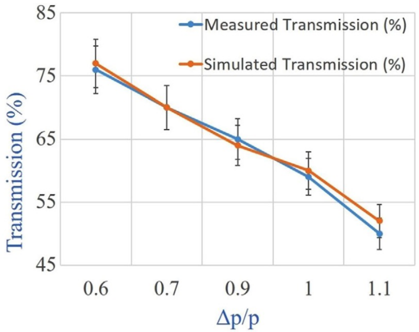
reproduces non-Gaussian-like overlaps matching the ATF2 laserwire experimental data

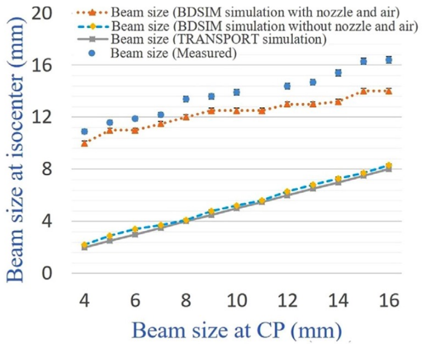
Medical Facility Application of BDSIM

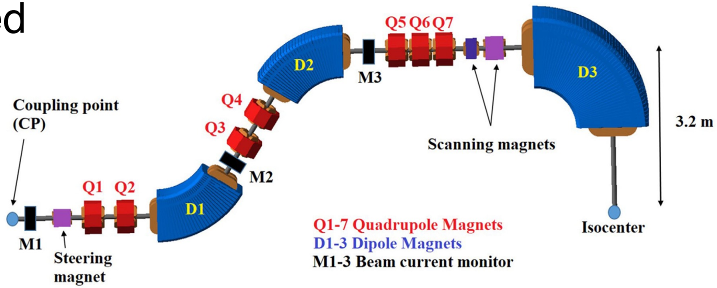
- We have developed BDSIM for low-energy applications since 2017 and are now seeing uptake in the community for medical applications
  - suited for particle-matter interactions in beam lines and that often have relatively high losses
- Several groups in PSI, Hefei China using BDSIM for medical design studies
  - PSI Gantry 2, SC200 proton facility
- Recent publications showing excellent agreement with real facilities
  - transmission / losses, beam profile
- Recent PSI publication on transmission optimisation for FLASH therapy
  - becoming possible to deliver field in single breath-hold
- Link with IBA stable, upcoming studies on:
  - repurposing high-energy facilities for eye treatment
  - cross-talk between adjacent gantries for high-intensity research centres

An Example of Recent Results

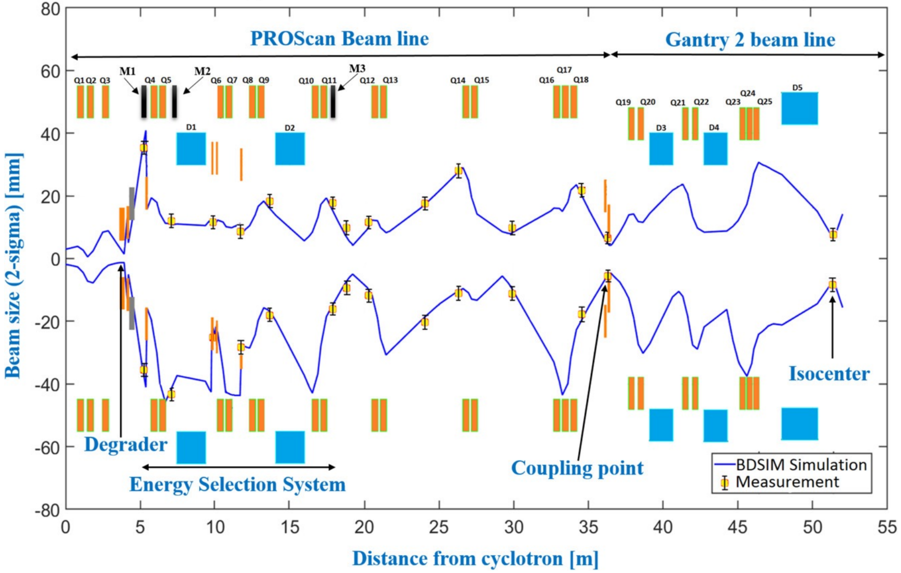
- PSI designed new emittance selection system to increase transmission by a factor of 6 for goal of FLASH therapy
  - https://doi.org/10.1002/mp.15278
- Also, new optics for PSI Gantry 2 for greater acceptance
  - https://doi.org/10.1002/mp.15505
- Goal of higher transmission
  - new optics and coupling point (CP)
- Excellent agreement with experiments achieved







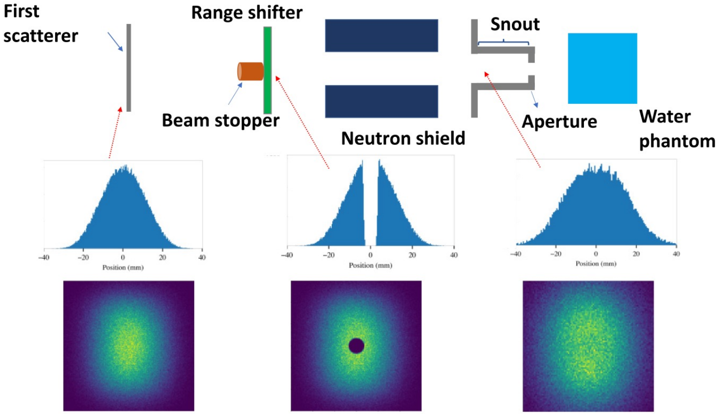
PSI Gantry2 Model

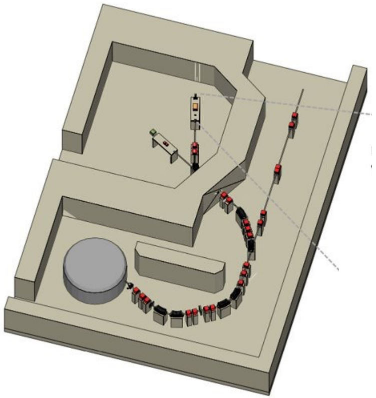


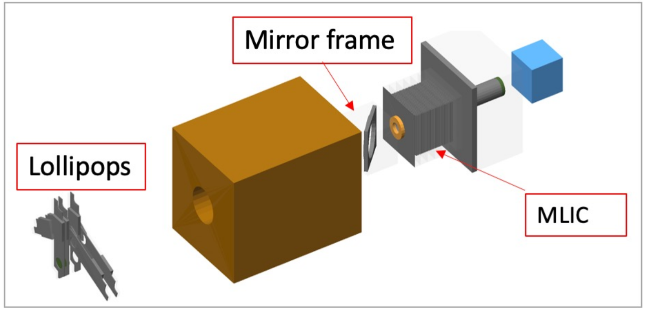
IBA Eyeline Studies

W. Shields, L. Nevay, C. Hernalsteens, ULB Group

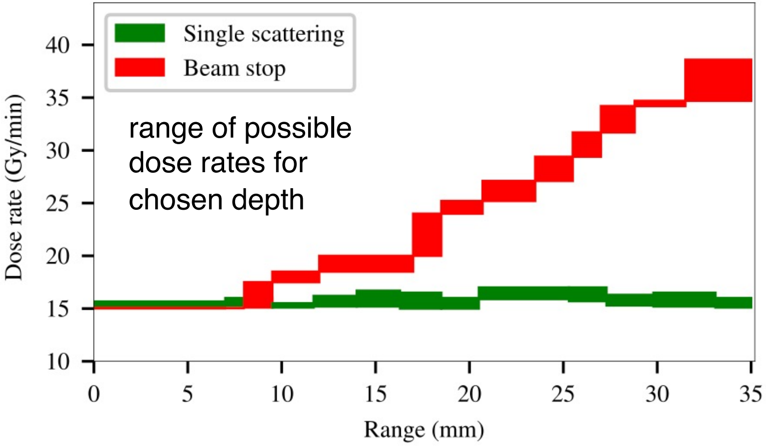
- IBA / ULB Study on increasing dose rate in eyeline
  - https://doi.org/10.1103/PhysRevResearch.4.013114
- Results: reduce distal fall-off and reduce treatment time by factor of 3: treatment in < 30s
  - huge improvement for patient holding still
- ULB contributing to new BDSIM features regularly







IBA Proteus©Plus Model with eyeline



Prospects for Industry with RT Simulations

L. Nevay, W. Shields, S. Boogert

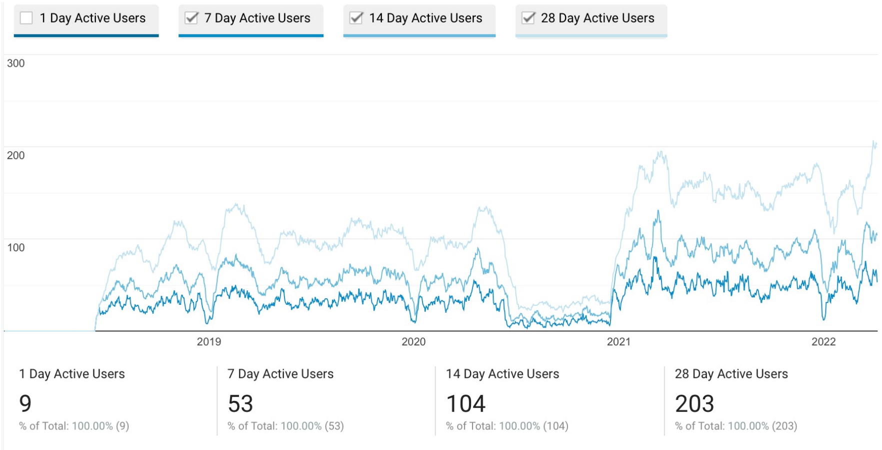
- Many links formed in past ~ 4 years
- Moving forward, the goal is to create impactful relationships
  - (most) software is publicly available, but our capability exceeds this
- Initial contact with Research Instruments for their project LightHouse
  - will produce Mo-99 (half-life 66 hrs) source -> Te-99 (half-life 6 hrs)
  - without relying on nuclear waste as a source
  - discussions underway on possible joint project / studentships
- Contacted by Space Talos - UK satellite shielding company
  - 1 week consultancy so far on Geant4 physics extension based on LHC research
  - further consultancy in 2022 and also through Horizon bid (application ongoing)
  - website: https://spacetalos.com
- Setting up a BDSIM Collaboration managed by RHUL to permit academic contribution but a set of defined beneficiaries from any commercial activity

John Adams Institute for Accelerator Science

Thank you for your attention

BDSIM Manual Usage

- We don't track software usage
  - can't do this easily in line with academic research and be open-source
- Google analytics for website visits
  - usual publicly available information from browser
  - good idea of usage in cities with facilities
- Software open source but must cite paper



website hits by city in last year