A UK Perspective on Future High Energy Colliders

Prof Stewart T Boogert (John Adams Institute @ Royal Holloway)

Institute of Physics, Joint Annual HEPP and APP conference

21st March 2016, University of Sussex

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Talk outline

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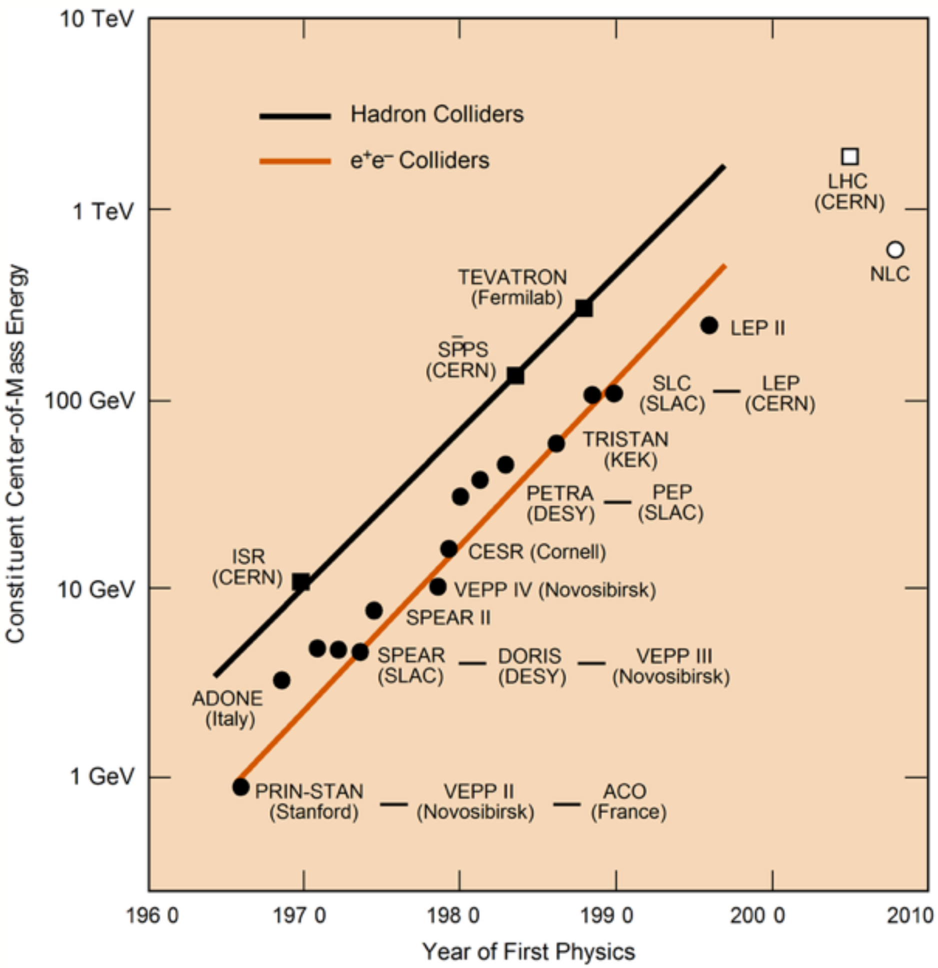
- IoP2014 (V. Shiltsev : 100 TeV, F. Zimmermann : FCC-ee)
  - Projects need to be truly global, funding a problem
- IoP2015 (P. Ratoff, Future of Accelerators)
  - Novel accelerator technology might be an answer, also funding is a problem
- **Talk focused on UK activities**
  - Incomplete, flavor of the UK's position towards numerous potential facilities
- Future machines
  - High luminosity Large Hadron Collider (HL-LHC)
  - International Linear Collider, Compact Linear Collider (ILC, CLIC)
  - Muon collider
- Future Circular Collider (FCC)
- Advanced concepts
  - Laser and beam driven plasma accelerators

Accelerator Livingstone Plot



- Progress towards high energies limited
  - Circular machines ⇒ Synchrotron radiation (electron) and bending field (protons) limit
  - Linear colliders a technical solution ⇒ high construction and operation costs limit

Rationale for future colliders

- Choice for a future machine
  - Clear LHC results will dictate the choice for future facility
  - Energy reach is not the only consideration
    - Luminosity, polarisation, staging, stability, power consumption (efficiency)
  - Higgs/top factory
    - International linear collider (also CLIC)
    - Muon collider
  - Current LHC results point towards
    - HE-LHC to FCC
    - 3 TeV CLIC

UK accelerator physics, universities and institutes landscape

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- UK has two strong accelerator institutes
  - John Adams Institute (Oxford, Imperial & RHUL)
  - Cockroft Institute (Manchester, Liverpool & Lancaster)
- University groups
  - Imperial College
  - University of Huddersfield
  - University College London
  - University of Strathclyde

UK expertise and competences

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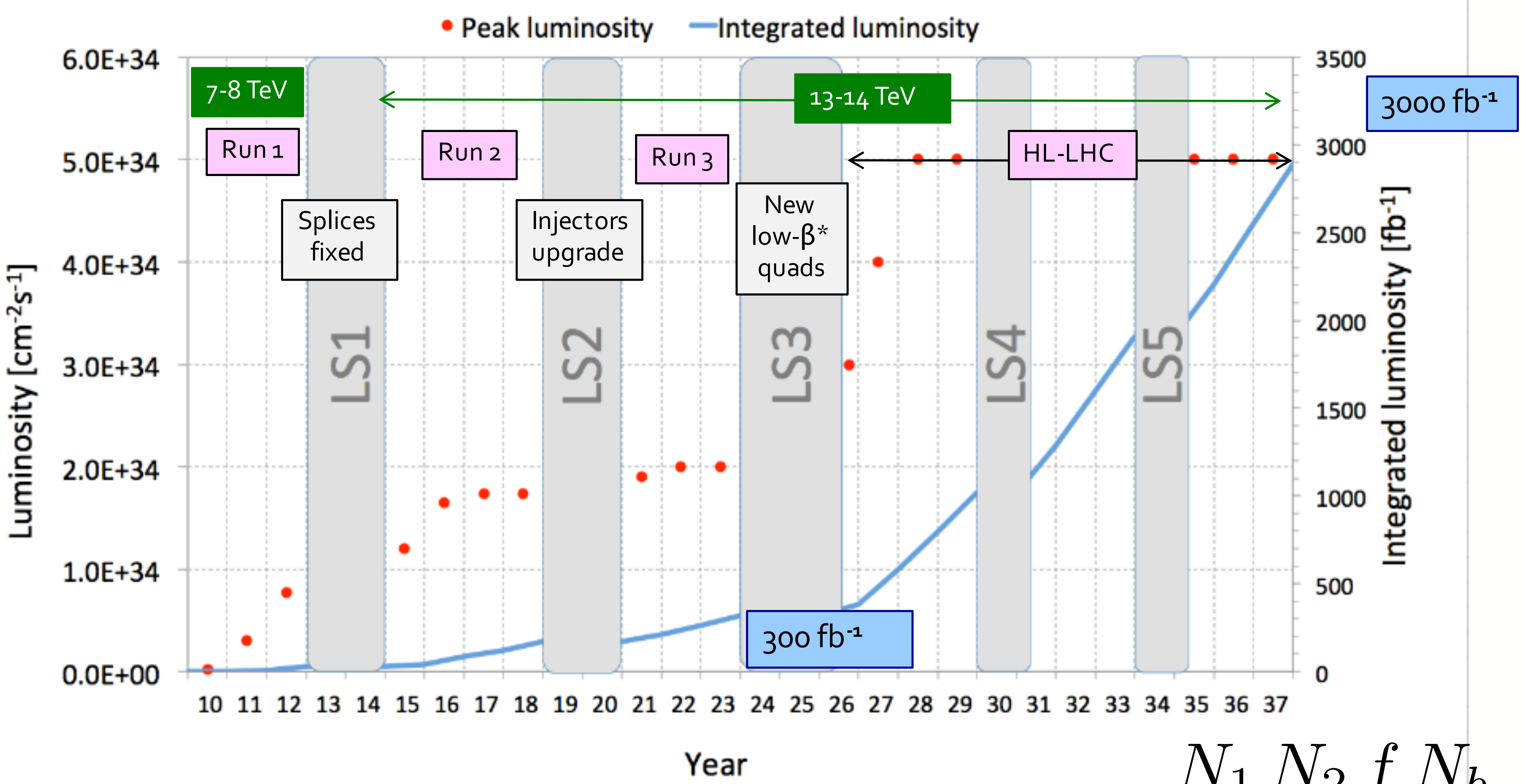
- Beam instrumentation and control
- Beam dynamics
- Simulations, beam losses and collimation
- Machine detector interface and interaction regions
- Accelerating structures
- Plasma wake-field acceleration

LHC/HL-LHC medium term future



$$\mathcal{L} = \frac{N_1\, N_2\, f\, N_b}{4\pi\sigma_x\sigma_y}$$

LHC injector upgrade

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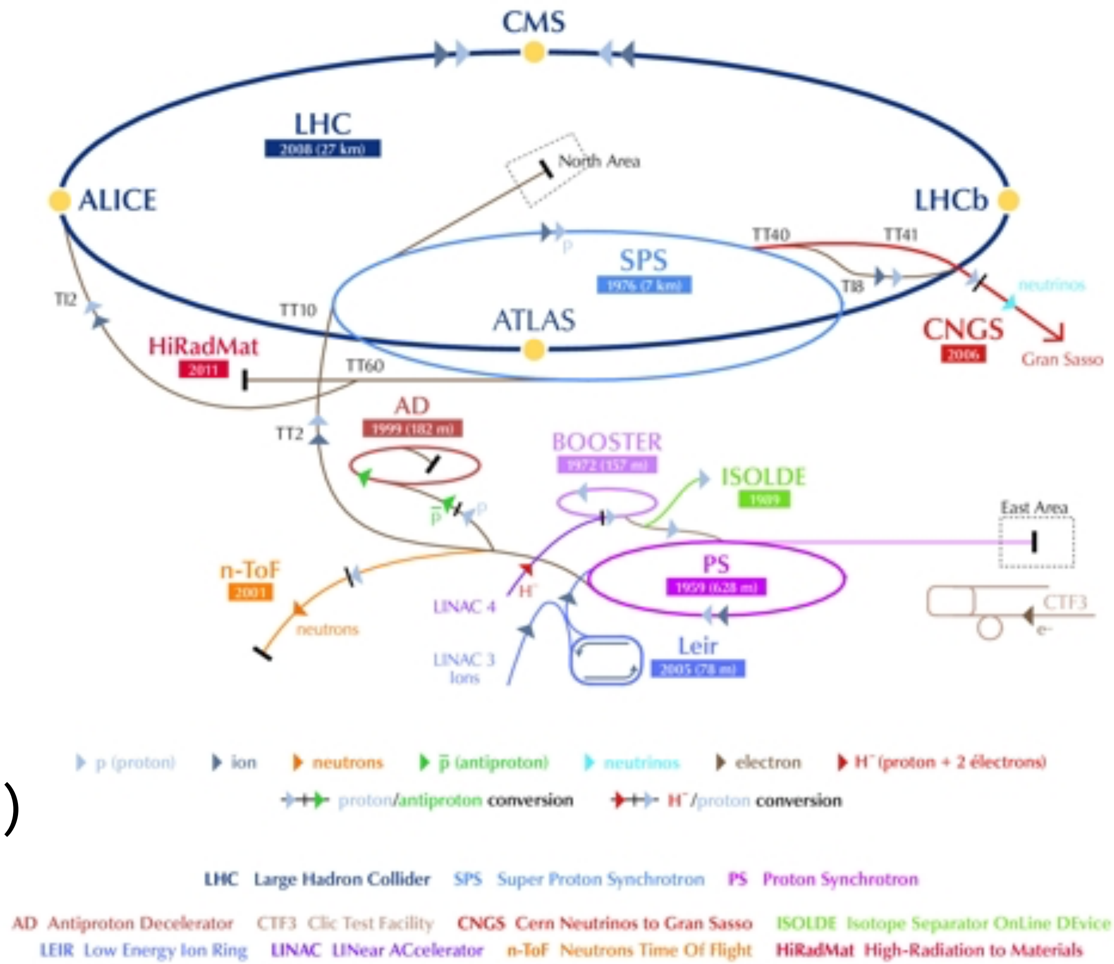
- Reliability and performance of injector chain
  - LINAC4 (superconducting 160 MeV H^- linac)
  - Booster (50 to 160 MeV injection)
  - PS (1.4 to 2 GeV injection)
  - SPS (transverse feedbacks)



High luminosity Large Hadron Collider

$$\mathcal{L} = \frac{N_1 \, N_2 \, f \, N_b}{4\pi\sigma_x\sigma_y}$$

- New IR-quads Nb_3Sn [inner triplets]
- New 11 T, Nb_3Sn [short dipoles]
- Collimation upgrade (Manchester, RHUL)
- Cryogenics upgrade
- Crab cavities (Lancaster)
- Cold powering (Southampton)
- Machine protection

Collimation studies (Manchester, RHUL)

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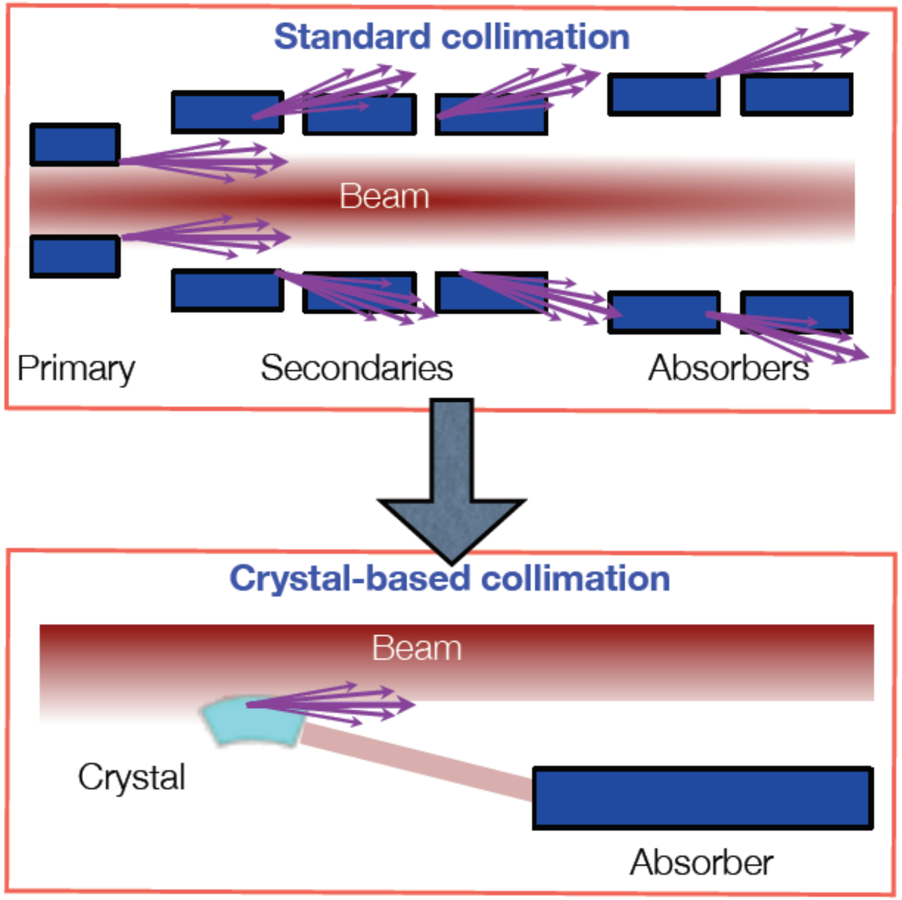
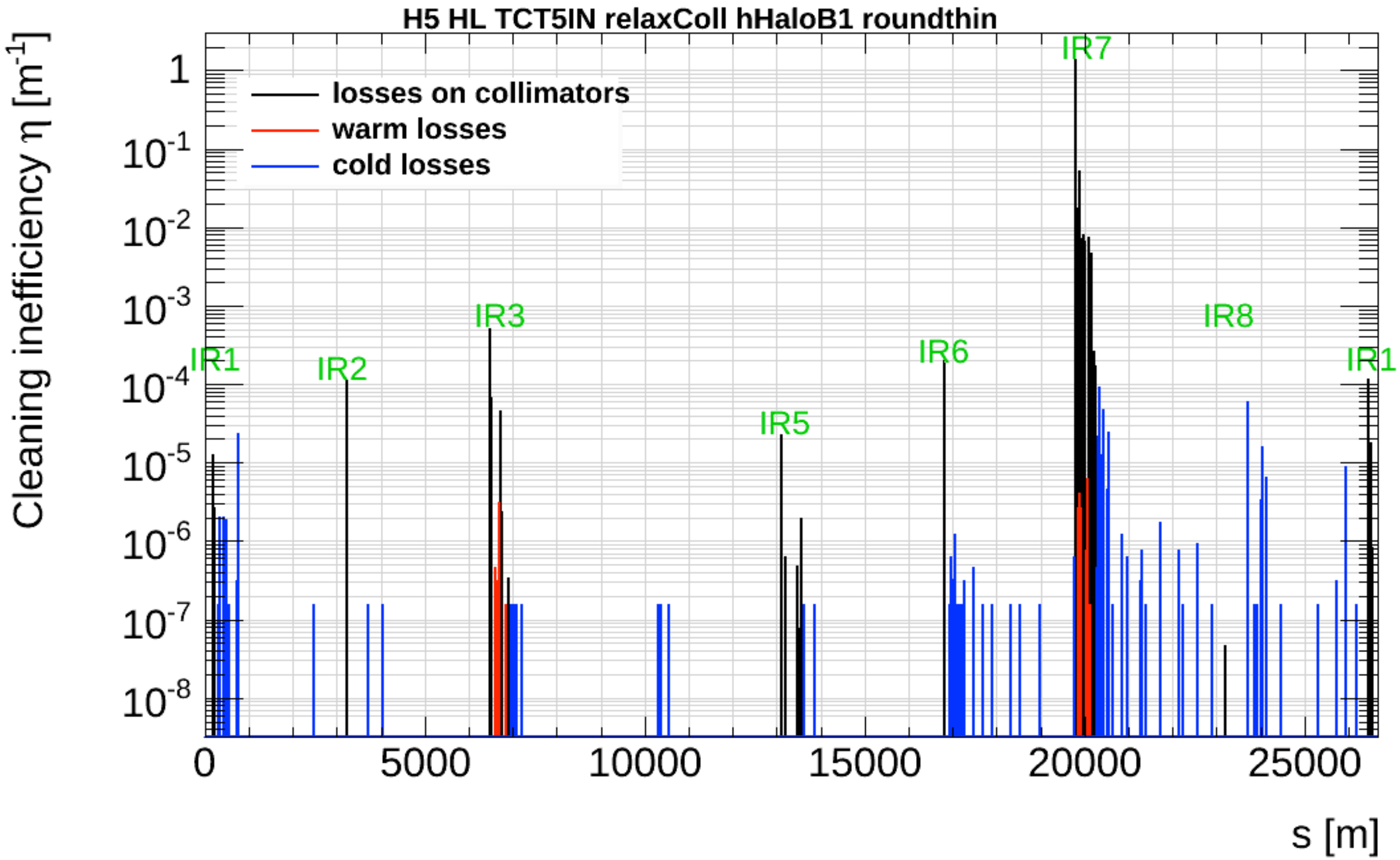


- Increasing the beam current increases the losses
  - Collimation system key to protect superconducting magnets
  - Simulate beam interaction will collimators
    - 7 TeV scatter
    - Track particles in LHC

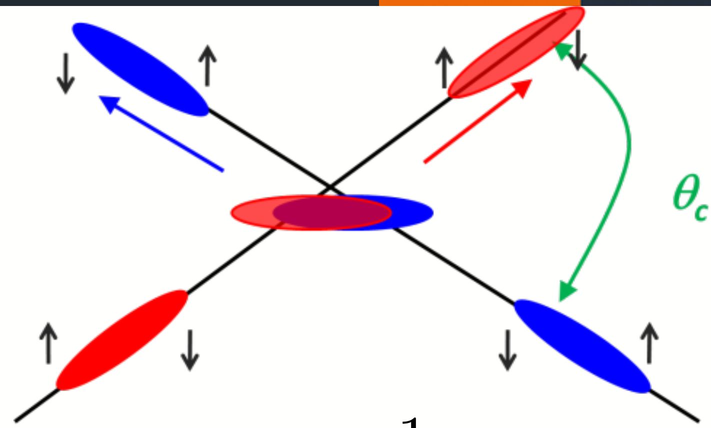
Beam losses



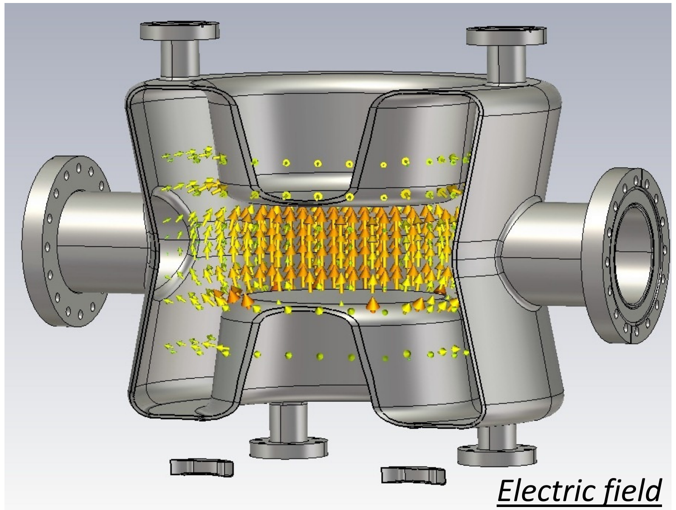
H5 HL TCT5IN relaxColl hHaloB1 roundthin
Cleaning inefficiency η [m^{-1}]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
losses on collimators
warm losses
cold losses
IR1
IR2
IR3
IR5
IR6
IR7
IR8
IR1
0
5000
10000
15000
20000
25000
s [m]

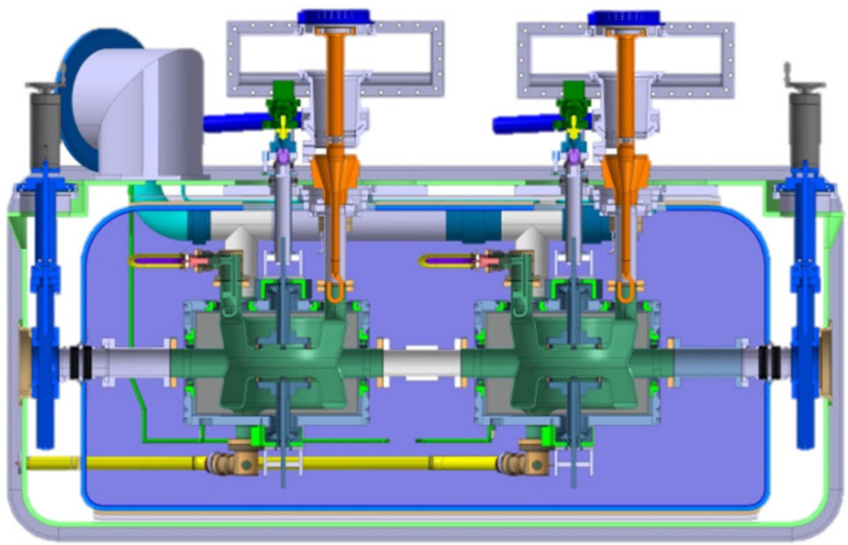
Crab cavities (Lancaster)

- Crossing angle (285 μrad) reduces luminosity at LHC
  - Rotate bunches by crossing angle to recover the head on collision luminosity



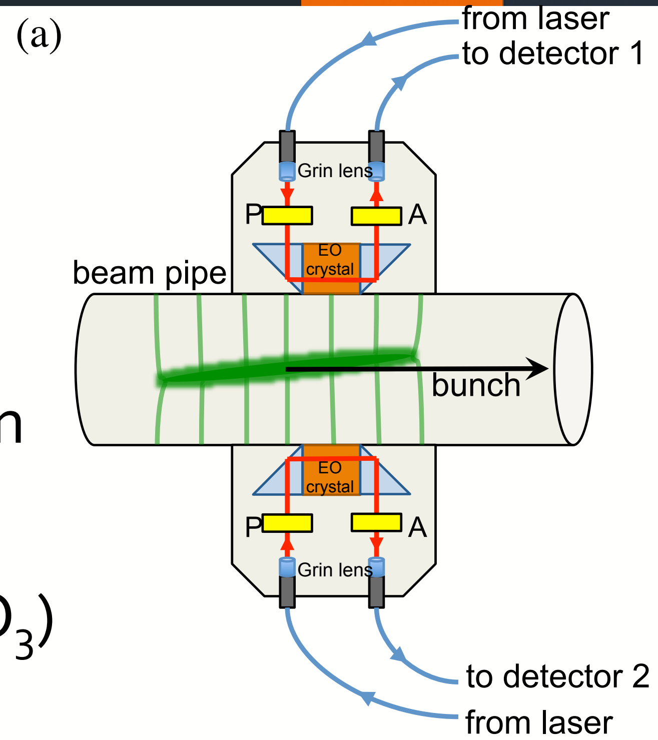
$$R(\theta) = \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x} tan\frac{\theta}{2})^2}}$$

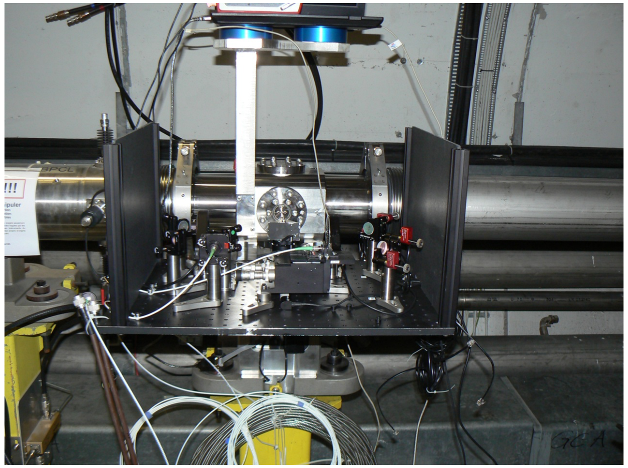


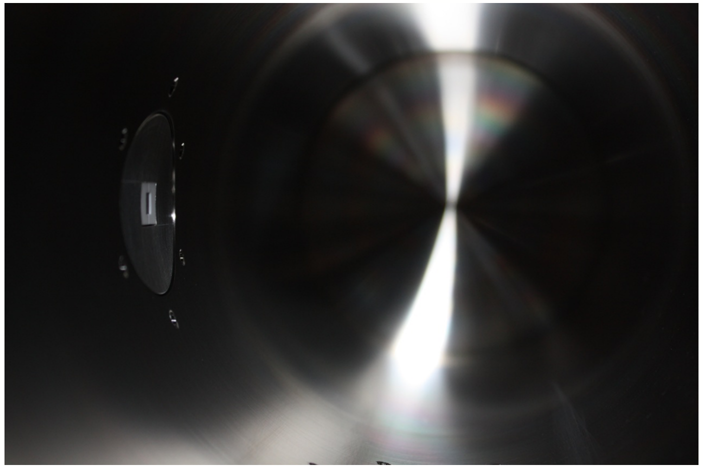


Crab diagnostics (RHUL)

- Rotation of such a rigid beam needs confirmation
  - Measure position along bunch length
  - Traditional instrumentation potentially can not measure at high enough bandwidth
  - Use electro-optical effect in crystal ($LiNbO_3$)

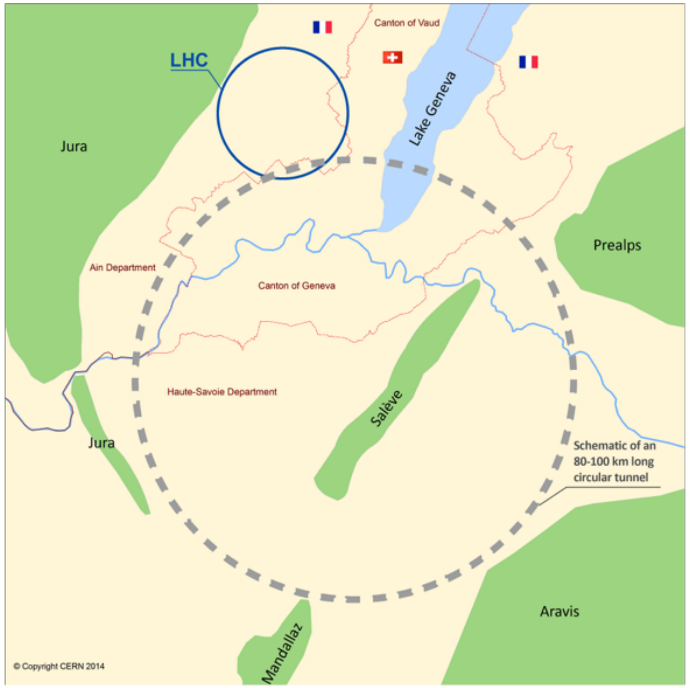






Future Circular Collider (FCC-hh)

- Scale LHC in energy by factor 8
  - Ring radius set by available dipole technology $$B \times r = \frac{p}{q}$$
  - Luminosity and losses (SR and collimation) proportional to beam current



Parameter	LHC	FCC-hh
Energy [TeV]	14	100
Dipole field [T]	8.33	16
#IP	4	2+2
Luminosity L [$cm^{-2}s^{-1}$]	1×10^{34}	$2\text{-}25\times10^{34}$
Stored energy/beam [GJ]	0.39	8.4
Synch rad [W/m/aperture]	0.17	28.4
Bunch spacing [ns]	25 (5)	25

International Linear Collider

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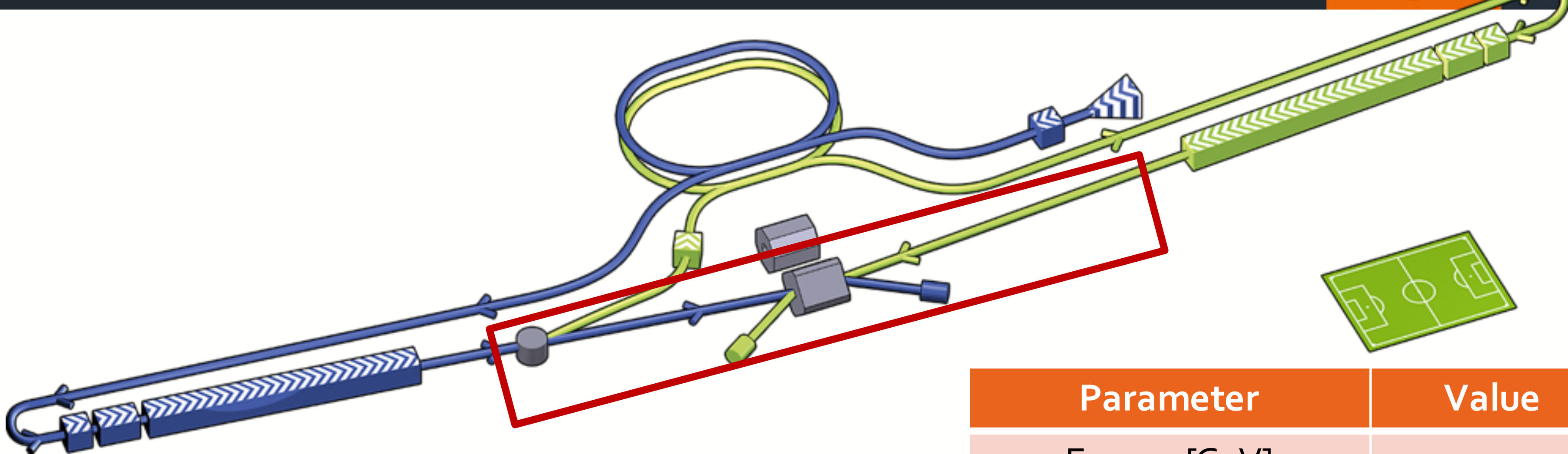
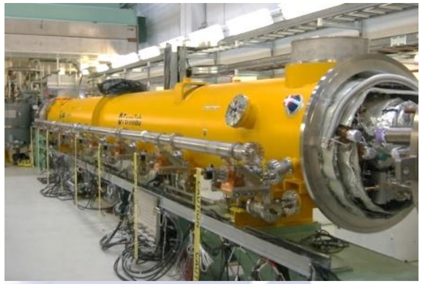


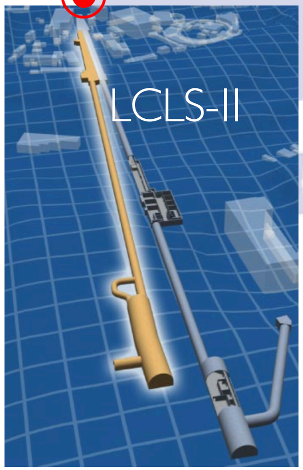
- UK groups focus on beam delivery system
  - Feedback systems, emittance measurement, beam position measurement
  - Optics and backgrounds

Parameter	Value
Energy [GeV]	500
Peak luminosity	1×10^{34} cm^{2}s^{-1}
Beam rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA
E gradient (SCRF)	31.5 MV/m
Number of SCRF 9 cell cavities	~8000
IP beam size (h/v)	474/5.9 nm



Largest deployment of this technology to date
- 100 cryomodules
- 800 cavities
- 17.5 GeV (pulsed)

FNAL/ANL
SLAC
Cornell
JLab
LAL/
Saclay
DESY
INFN Milan
IHEP
KEK
Kitakami
proposed site



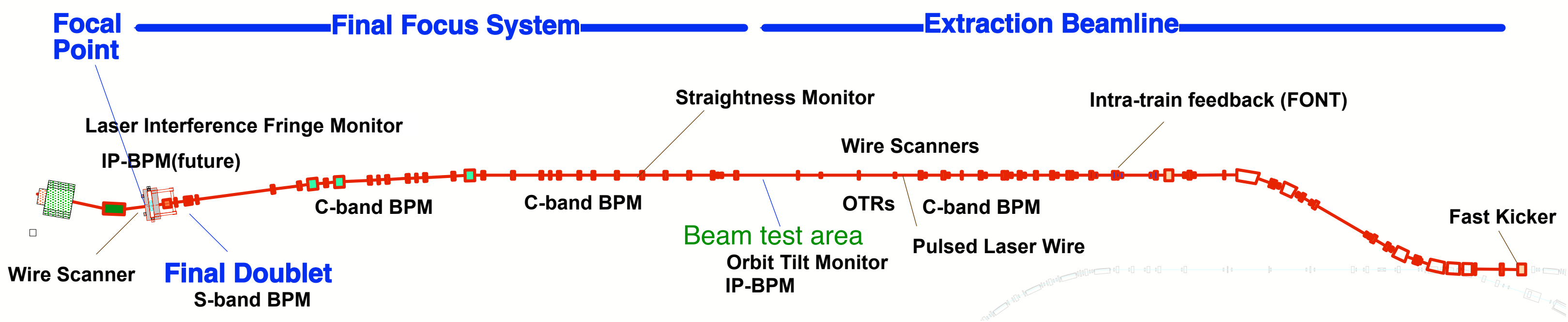
US infrastructure for
- 35 cryomodules
- 280 cavities
- 4 GeV (CW)

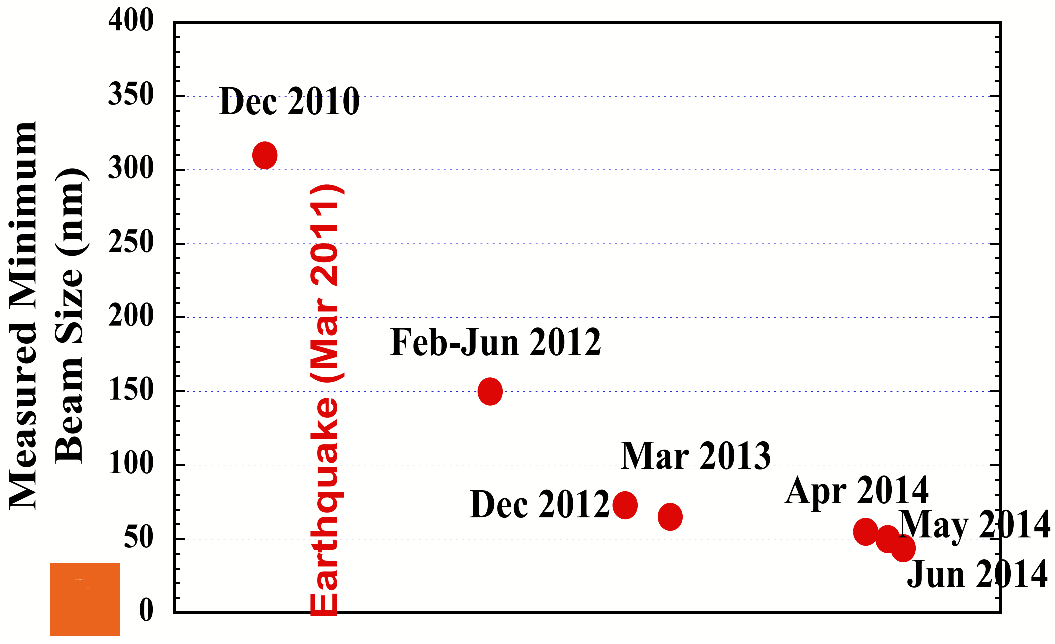
US and EU (industrial) production and test capacity. Perfectly placed for start of ILC construction end of this decade.

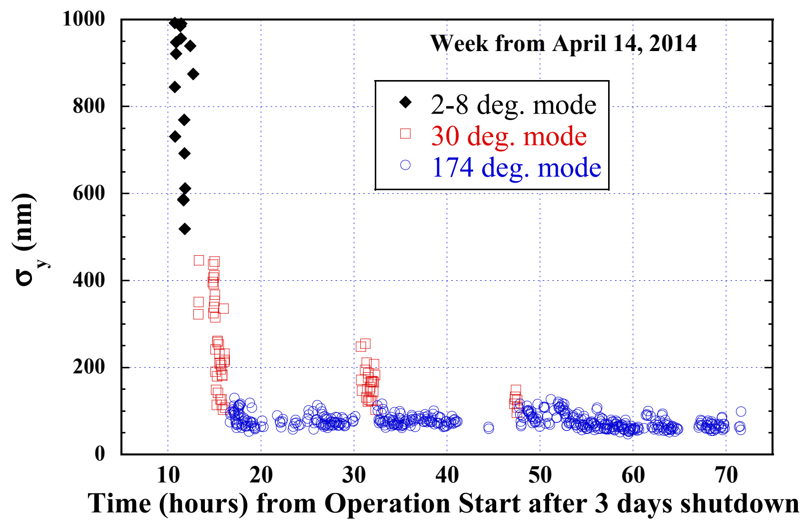
Nick Walker

Accelerator test facility

Beam Delivery system optics, instrumentation test-bed, tuning and feedback demonstration. Common interests for both CLIC & ILC. **Goal 35 nm vertical focus for 1.38 GeV beam**







ILC Japan siting (Iwate prefecture)

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Compact Linear Collider

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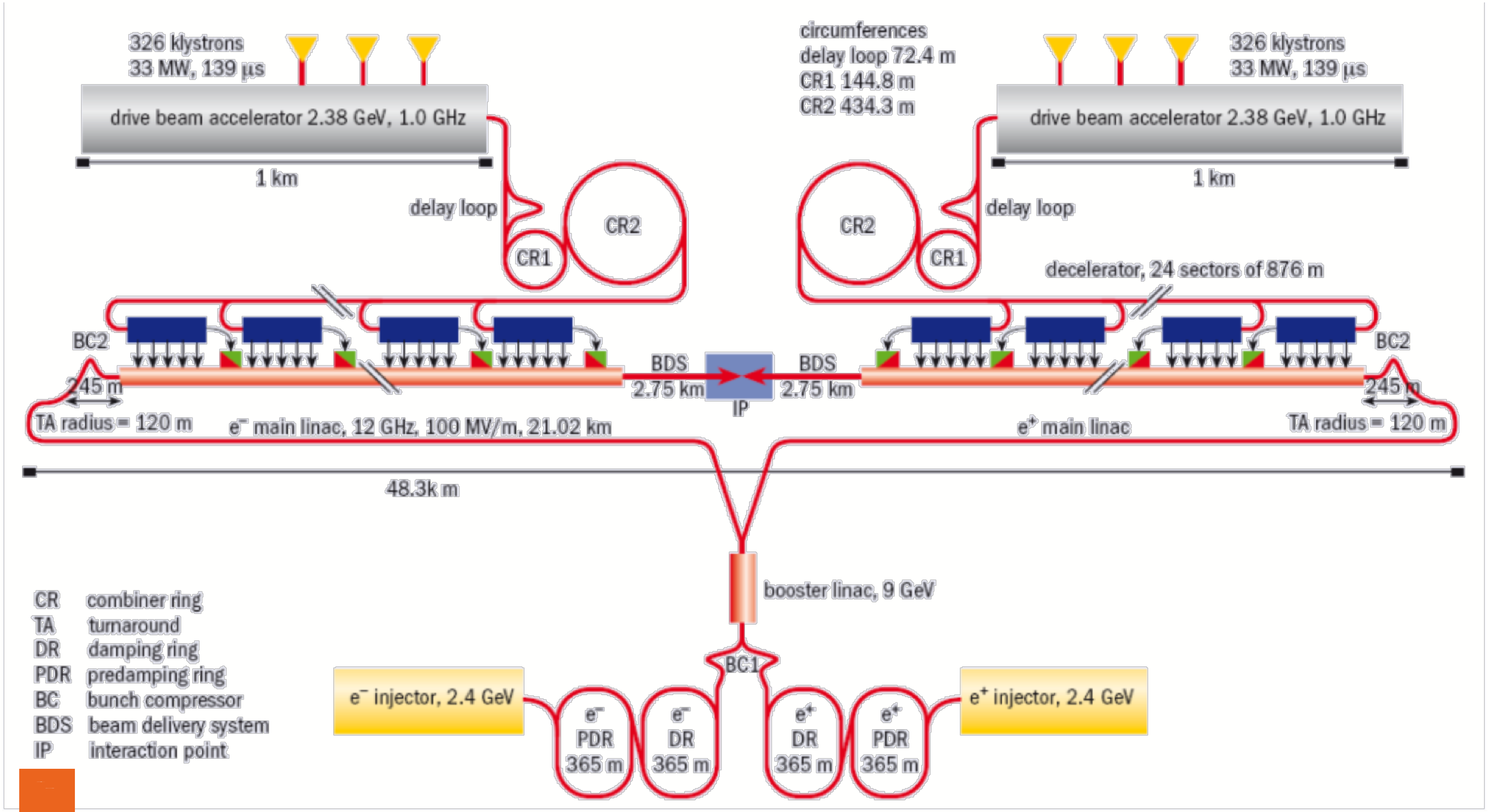
Two beam acceleration scheme, 2.38 GeV drive beam converted to RF power to accelerate main beam



Staged CLIC

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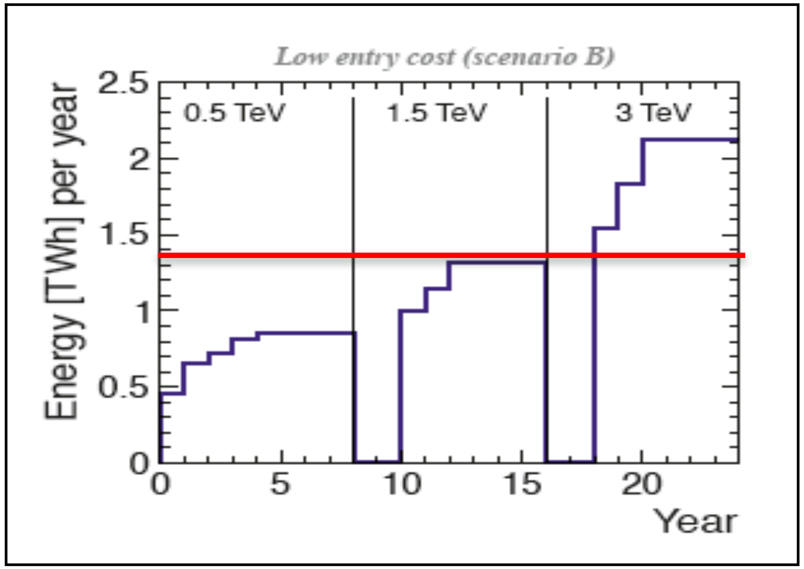
Parameter	Stage 1	Stage 3	Stage 2
Energy [GeV]	500	1500	3000
Rep frequency	50	50	50
Bunches per train	312	312	312
Luminosity *L* [10^{34} $cm^{-2}s^{-1}$]	1.3	3.7	5.9
IP beam size (x/y) [nm]	100/2.6	60/1.5	40/1
Gradient [MeV/m]	100	100	100
Tunnel length [km]	11.4	27.2	48.3
Power consumption [MW]	235	364	589



UK involvement in CLIC

- Crab cavities (Lancaster)
- Accelerating RF structure design (Manchester)
- Beam instrumentation (common with ILC)
    - Stripline beam position monitors (Oxford)
    - Optical diffraction radiation beam size measurement (RHUL)
    - Cavity beam position monitors (RHUL)
    - Longitudinal beam profile (Dundee)
- Drive beam phase feed-forward (Oxford)
- Magnet design (ASTeC)

Drive Beam Permanent Magnet Quadrupoles

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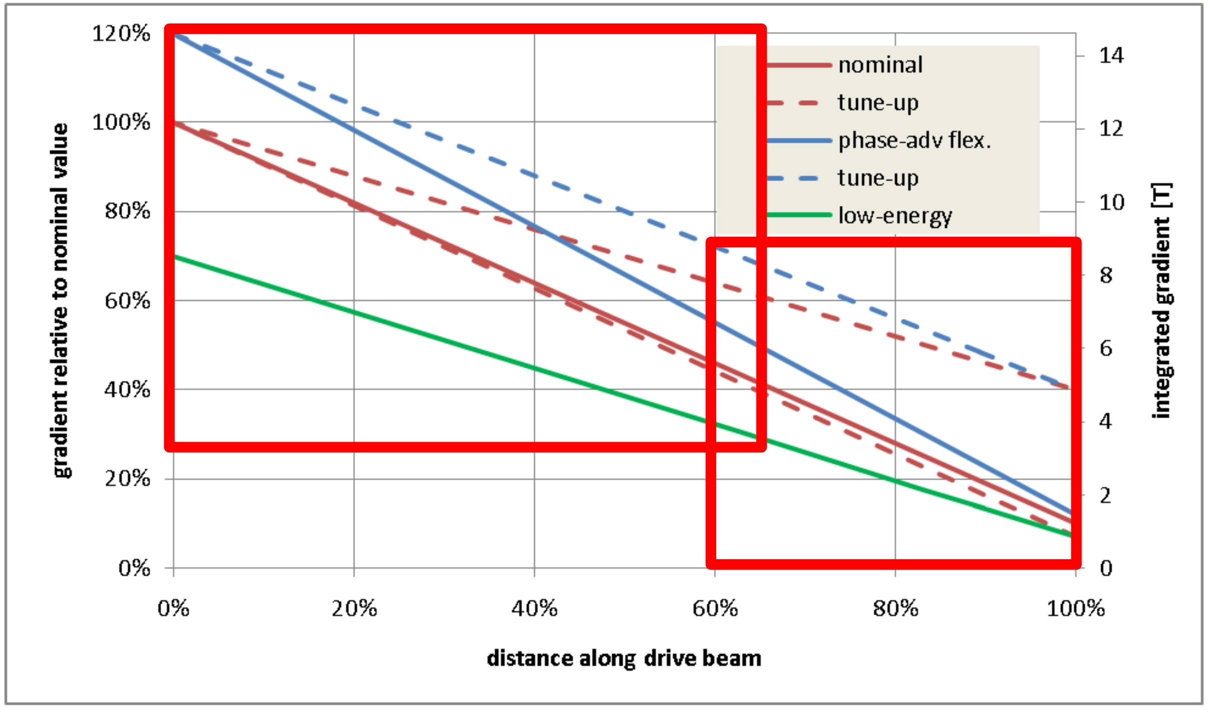
- Drive beams require ~50,000 magnets
  - Use permanent or hybrid magnets
  - Tuned by motion of permanent magnets
  - Two types : low and high energy quads



ASTeC magnet design

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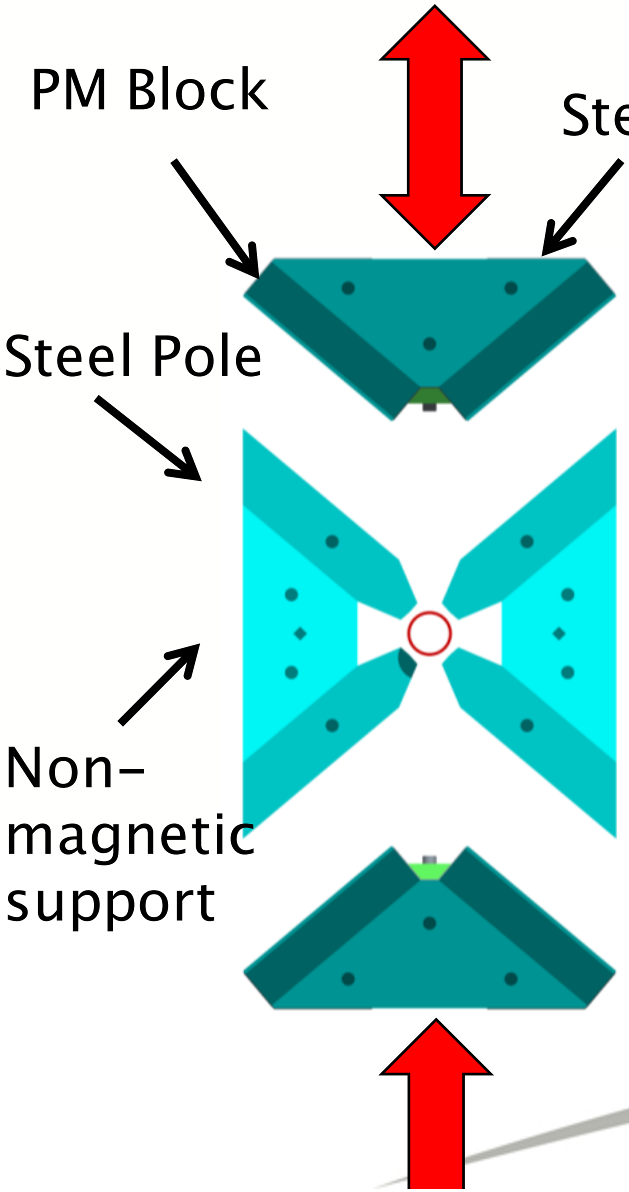
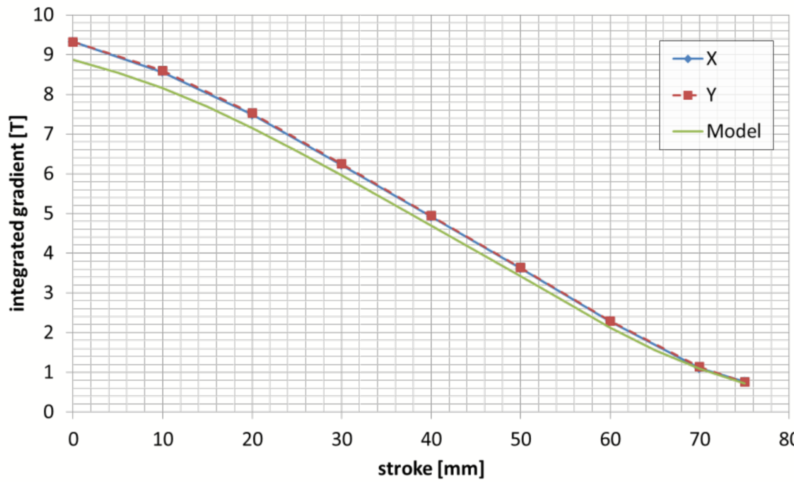
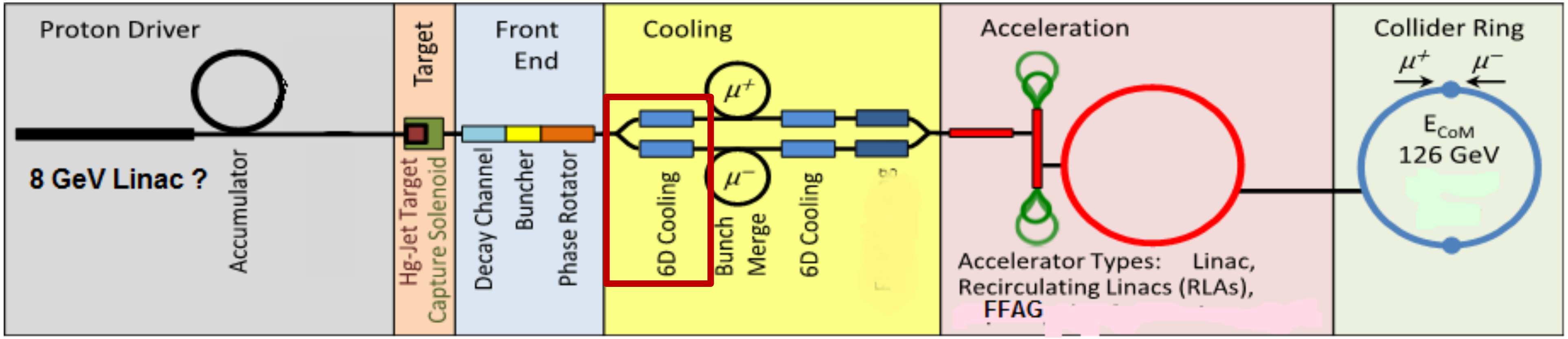


Low energy quadrupole



Science & Technology Facilities Council

Muon collider



- Avoid synchrotron radiation losses and use muons
- Production of muons does not result in a particle beam compatible with acceleration
- UK significantly involved in muon cooling experiments

Muon Ionisation Cooling experiment (IC/RAL/Ox)

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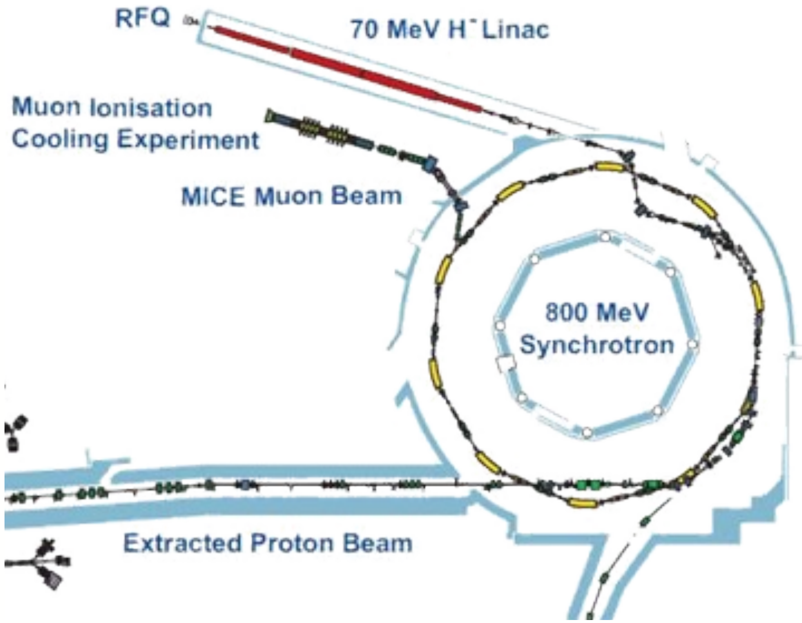
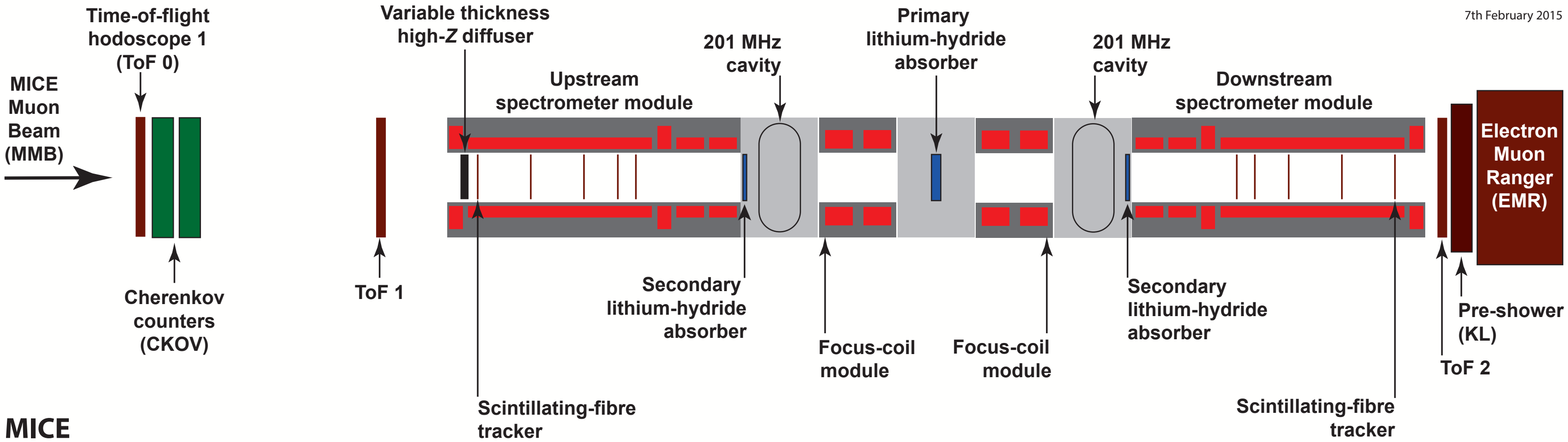
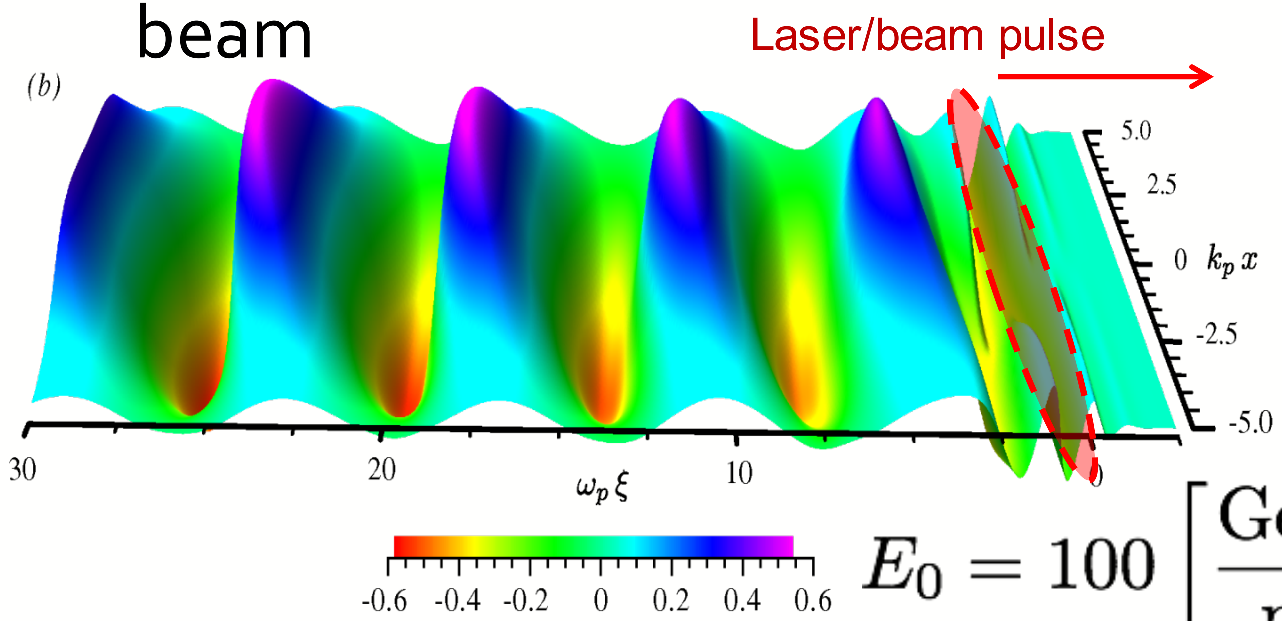
- Sited in Rutherford Appleton Laboratory
  - Muons produced from ISIS 800 MeV synchrotron
  - Reduce momentum (ionisation) and accelerate in beam direction





Plasma wakefield accelerators

- Excite wave in plasma using either laser or particle beam



$$E_0 = 100 \left[\frac{\text{GeV}}{\text{m}}\right] \sqrt{n_0 \left[10^{18}\text{cm}^{-3}\right]}$$

Driver	n_o	E_o	λ_p
Laser driven	10^{17} cm^{-3}	30 GeV/m	100 µm
Beam (e/p) driven)	10^{-18} cm^{-3}	100 GeV/m	30 µm

AWAKE (UCL/CI/IC/JAI/UoS)

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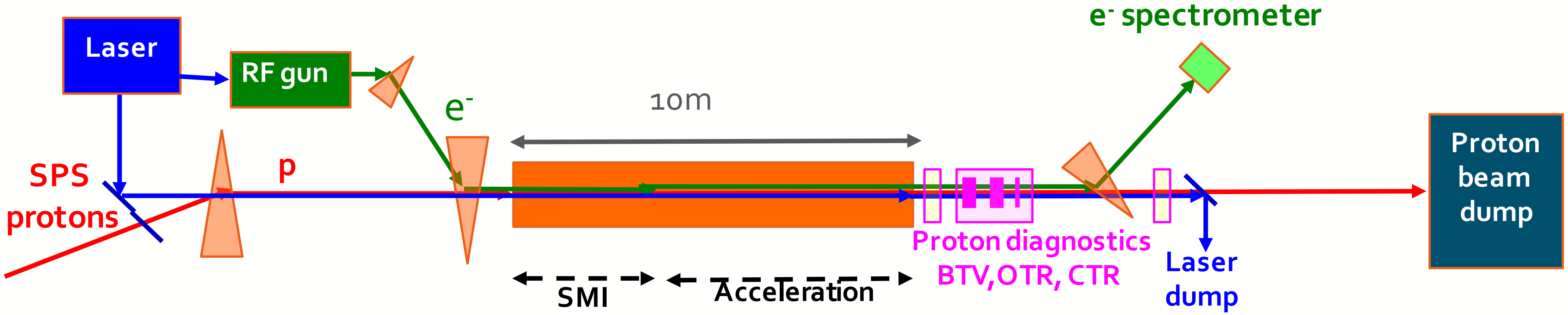

- Drive beam 400 GeV SPS proton beam
- Plasma Rb vapour source
- Laser beam 4.5 TW, ionises plasma and seeds self-modulation instability
- Electron witness beam 16 MeV/c, 1.2×10^9 electrons, σ=4 ps

AWAKE (Proton driven wakefield acceleration)

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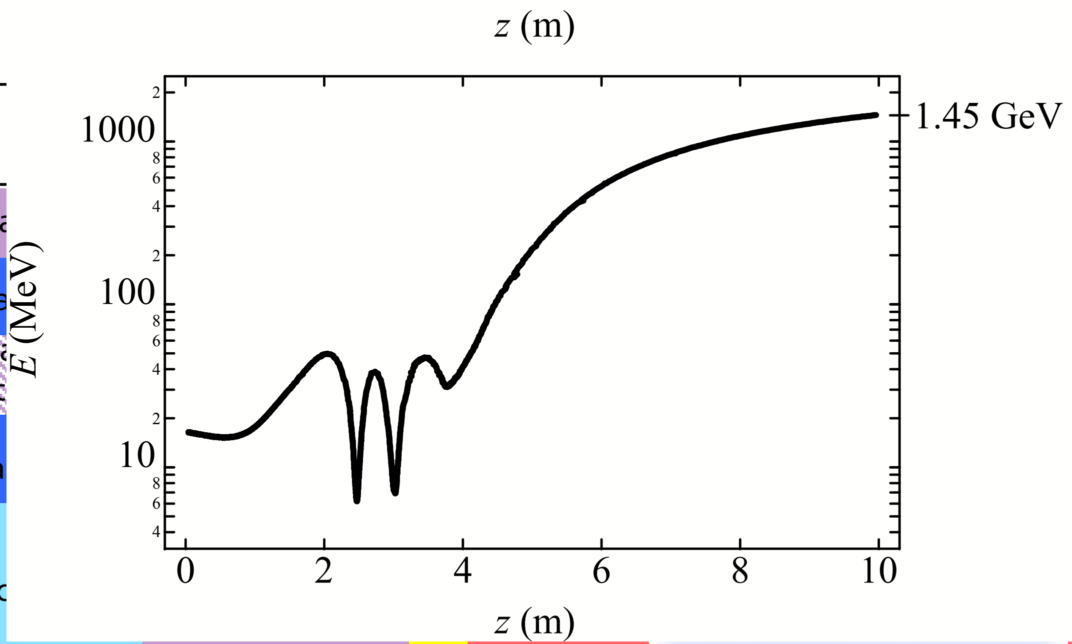
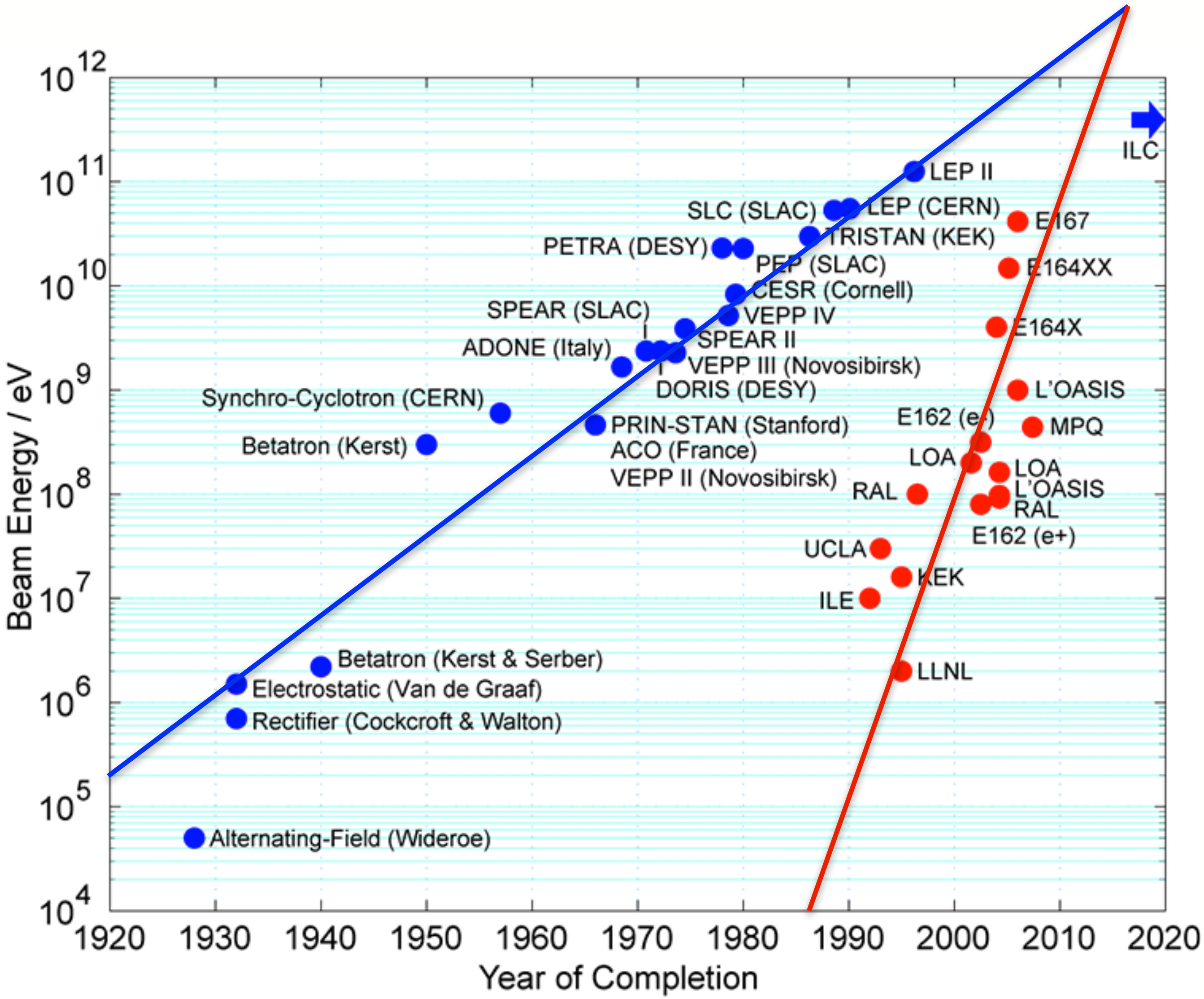
- Phase 1 : Understand **the physics of self-modulation instability** processes in plasma
- Phase 2 : **Probe the accelerating wakefields** with externally injected electrons.

	2013	2014	2015
Proton and laser beam-line	Study, Design, Procurement, Component prepa		Installa
Experimental area	Modification, Civil Engineering a installat; Study, Design, Procurement, Component prepa		
Electron source and beam-line	Studies, design		Fabric



Conventional vs Plasma Livingston



Laser driven wakefield acceleration

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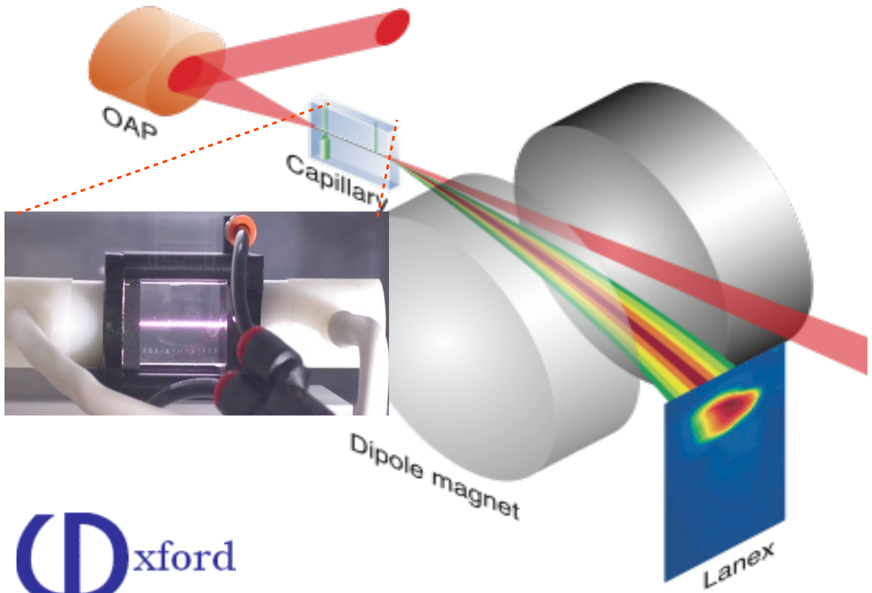
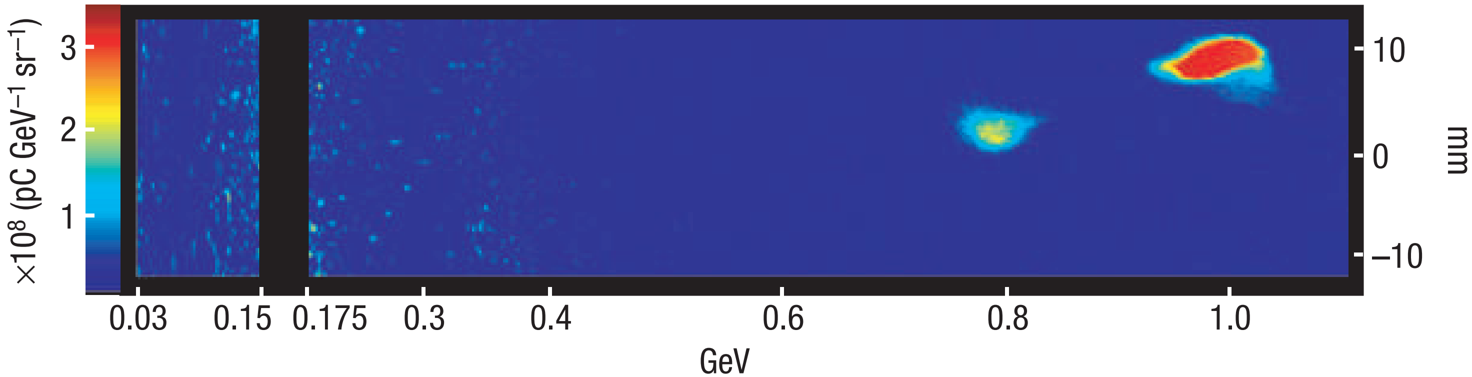
- Drive plasma using short high power laser pulse
  - Laser focusing in capillary
  - Losses between acceleration stages will not lead to significant luminosity
  - Efficiency of laser power sources does not match RF





Conclusions and summary

- UK involved in the majority of future collider projects
  - Current focus is HL-LHC
    - STFC/CERN funded work on HL-LHC
  - Historical strength in ILC and CLIC
    - Construction dependent on potential discoveries at LHC
    - Japan leading contender to site ILC, project is ready for construction
  - Discoveries at the LHC will spur continued involvement in numerous projects
    - AWAKE soon to produce physics results
  - New accelerator technologies are efficiency and luminosity limited
    - Can these problems be overcome for HEP applications?
- Ultimately progress is funded limited