The LHC Luminosity Upgrade and Related ATLAS Detector Plans

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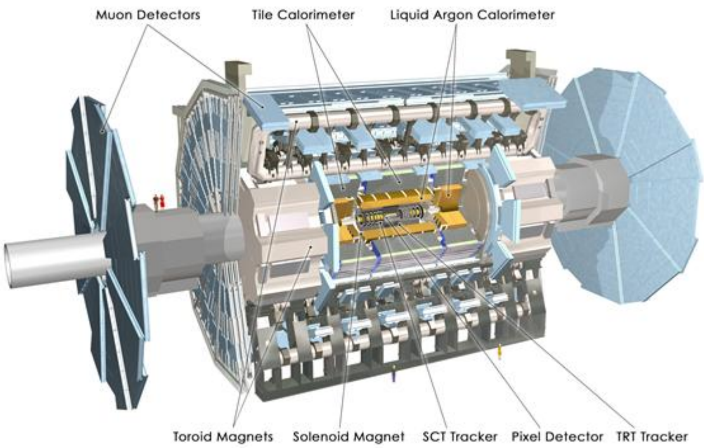
On behalf of the ATLAS Upgrade Steering Group

1st International Conference on Micro Pattern Gaseous Detectors

MPGD 2009, Kolympari, Crete, Greece, 12-15 June 2009

Overview

- Motivation of the LHC luminosity upgrade
- Progressing to sLHC
- Phase I and II in Atlas upgrade
- Upgrade activities on subdetectors
  - Muon system and calorimeters
  - Services
  - Triggering
- New inner detector
  - Developments in planar silicon
  - Alternative technologies for hottest parts (B-layer)
    - 3D silicon
    - Diamond
    - Gossip
- Conclusions



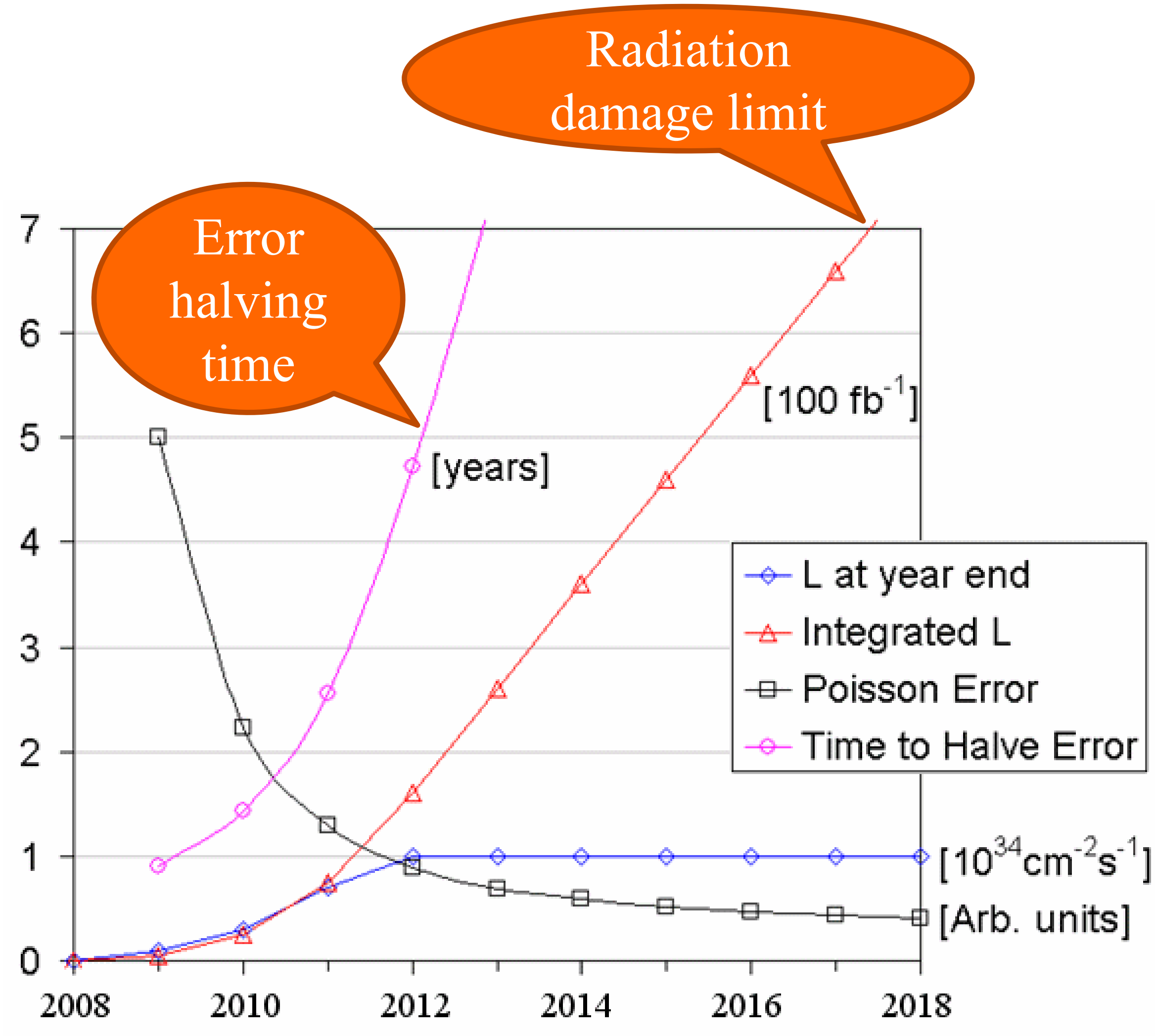
Why upgrade LHC?

- Instead of running at *constant* luminosity there're good reasons to *increase* luminosity

- Increasing beam energy not considered in near future
  - => replacing LHC

- Luminosity increase by 2-3 x 10^{34} $cm^{-2}s^{-1}$ occurring gradually **(phase I)**

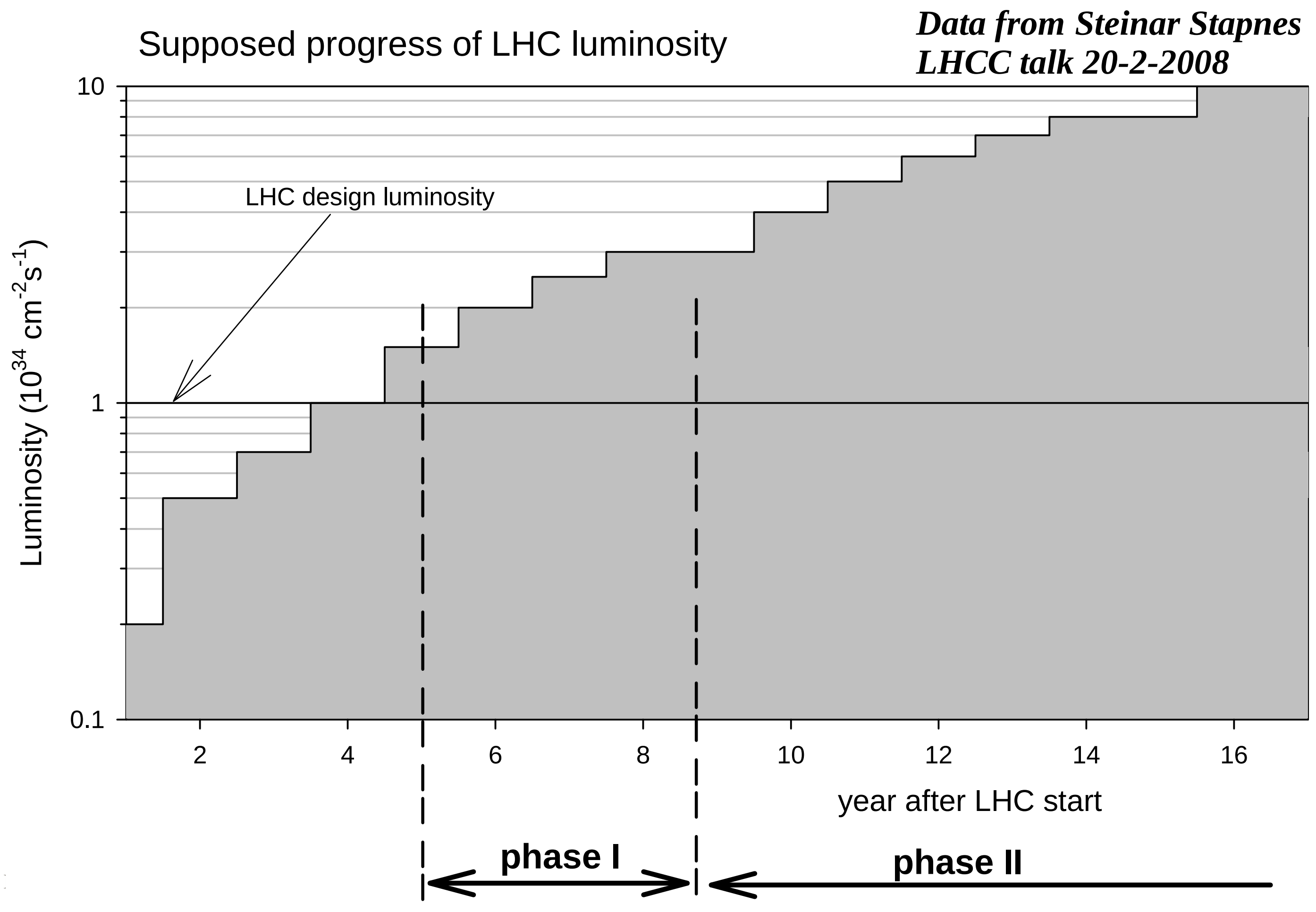
- For 10^{35} $cm^{-2}s^{-1}$ major modifications needed on machine and detectors **(phase II)**



R.Garoby, LHCC, July 1, 2008

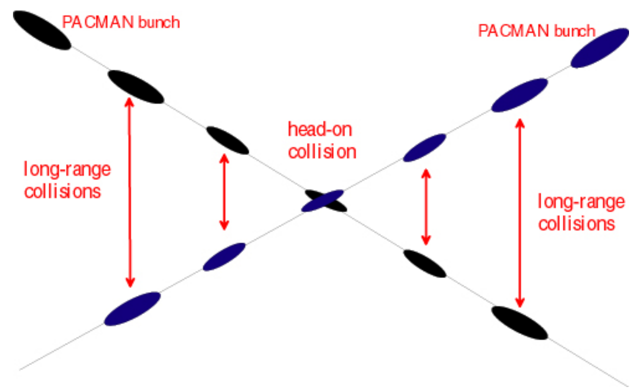
Supposed increase LHC luminosity

- Not few major steps but rather a semi continuous process with limited increase during maintenance periods

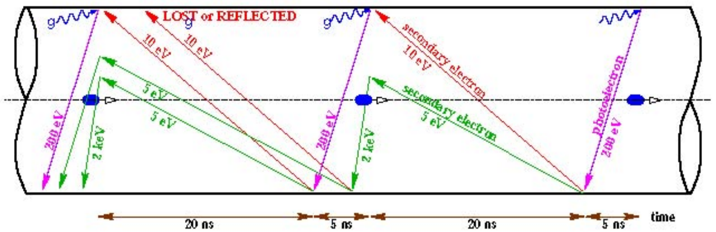


A few luminosity constraints present LHC

- Beam-beam interaction
  - electrostatic repulsion causing tuning deviation



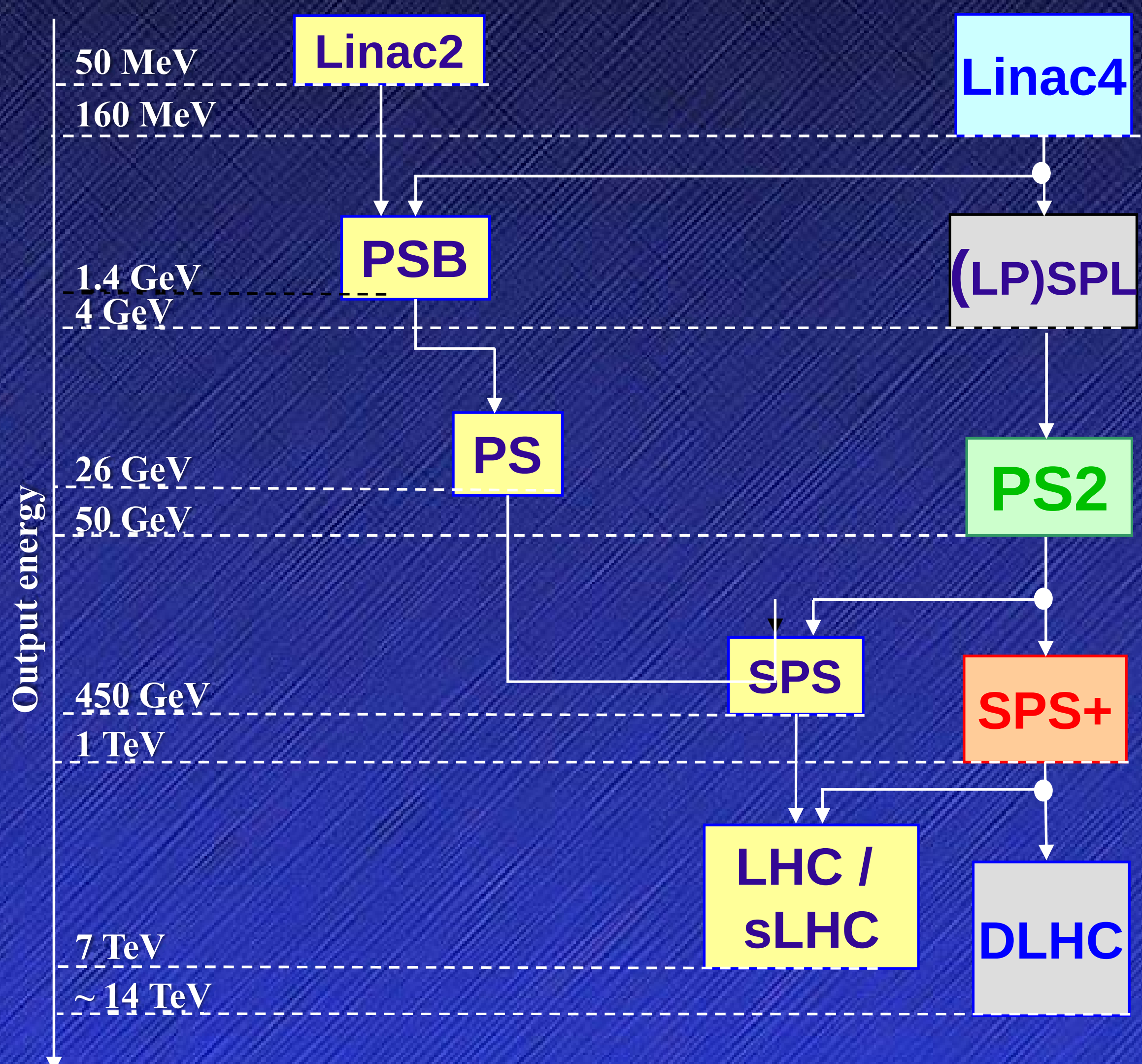
- Long range beam-beam effects
  - Electrostatic repulsion when beams approach each other
  - Until 9 σ beam separation
  - => affecting beam tuning => increased beam loss
- Collimation and machine protection: critical
  - 1% beam loss in 10 s at 7 TeV and full luminosity => 500 kW
  - 360 MJ stored in full LHC beam
  - Magnet quench limit 8.5 W/m
- Beam pipe heating due to electrons in the beam vacuum



F. Ruggiero

present and future injectors

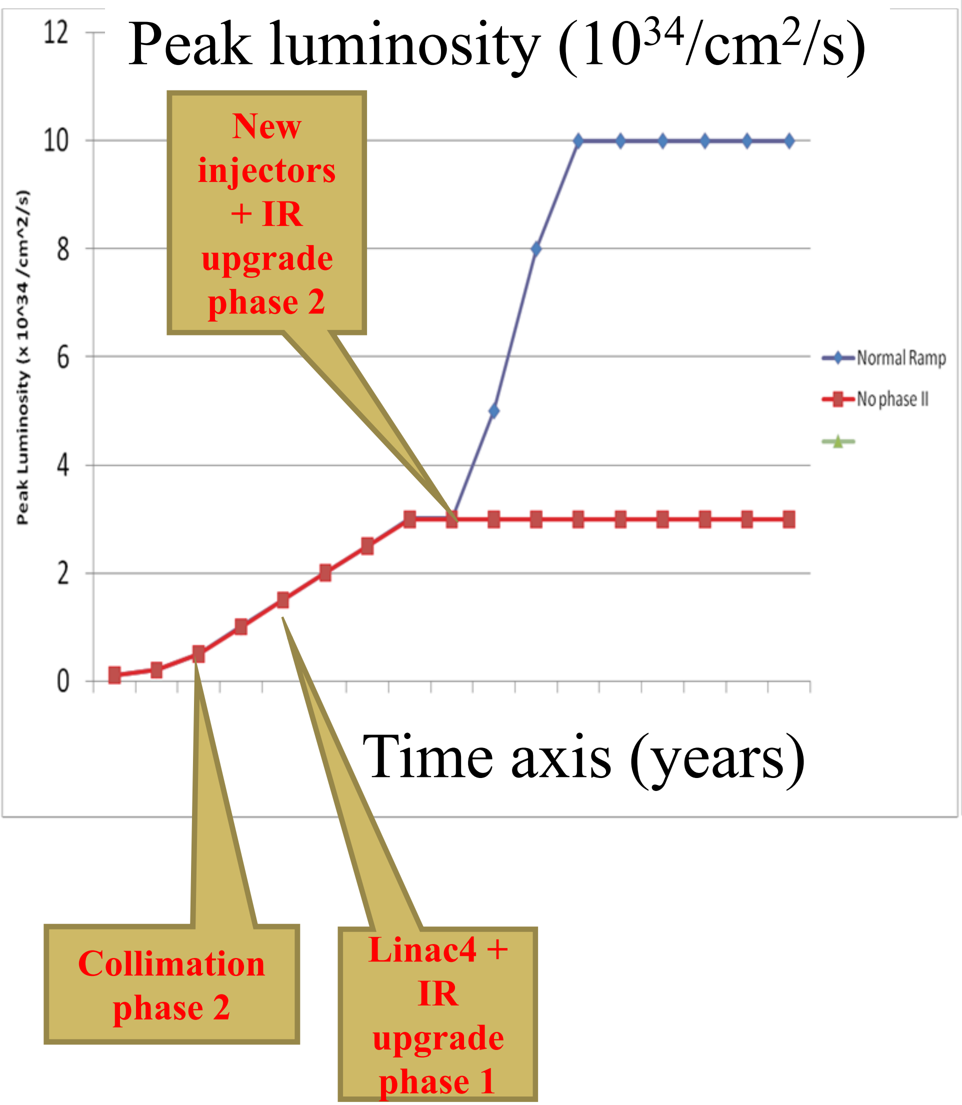
Proton flux / Beam power

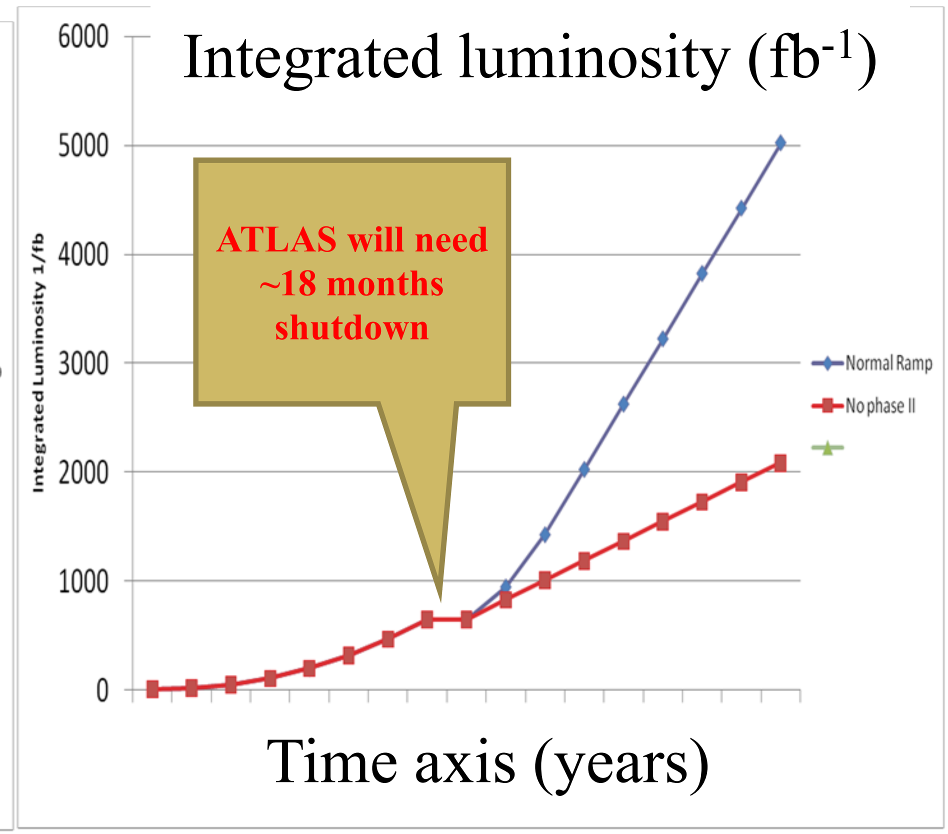


(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
sLHC: “Superluminosity” LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: “Double energy” LHC (1 to ~14 TeV)

Roland Garoby, LHCC 1July ‘08

Upgrade schedule





Frank Zimmermann, Feb. 27, 2009

When will this all happen?

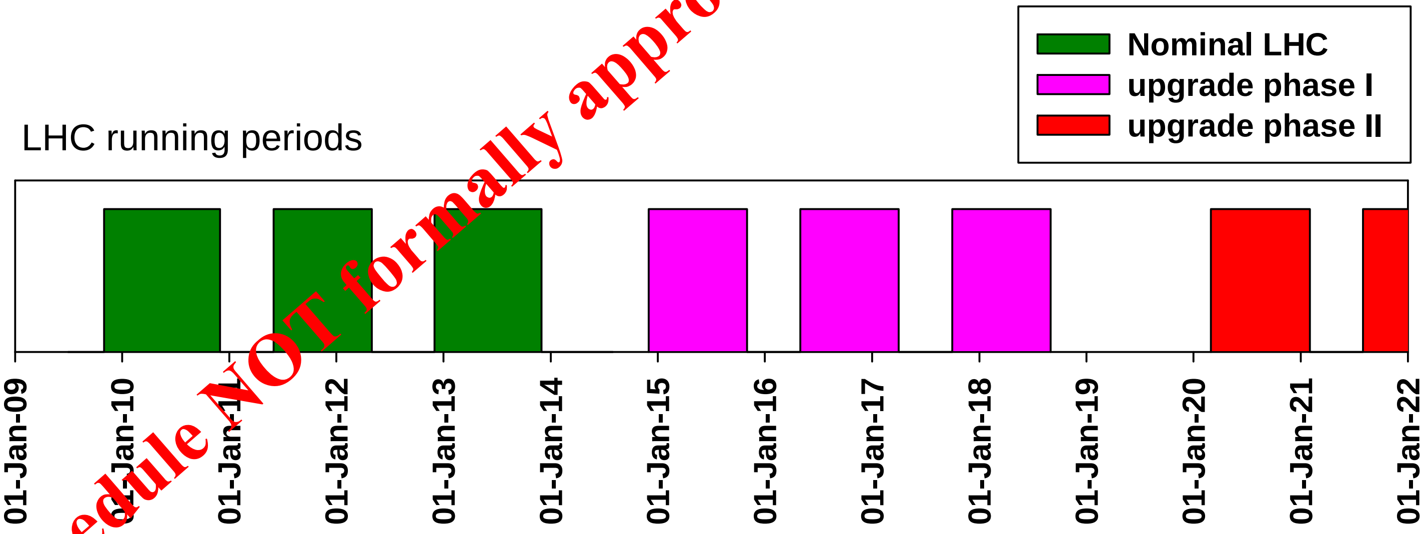
- Starting from known LHC starting date (Nov. 2009)
- CERN abolished 1st fixed winter shutdown
  - Possibly this will also be the case for the following running periods

1. IBL => based on what can realistically be achieved, Atlas aims for end 2014 (start of phase I)
2. If LHC Phase I appears to become earlier, then the programme will accelerated

LHC running schedule how it might be

- Assuming
  - Running periods of 11 – 12 months, followed by 6 months maintenance/ upgrade
  - We need three running periods to come to nominal LHC luminosity
  - We need three running periods in phase I to reach the 2-3 $*10^{34}$ cm^{-2} s^{-1} luminosity
  - ATLAS needs 18 months shutdown to install the full upgraded inner detector

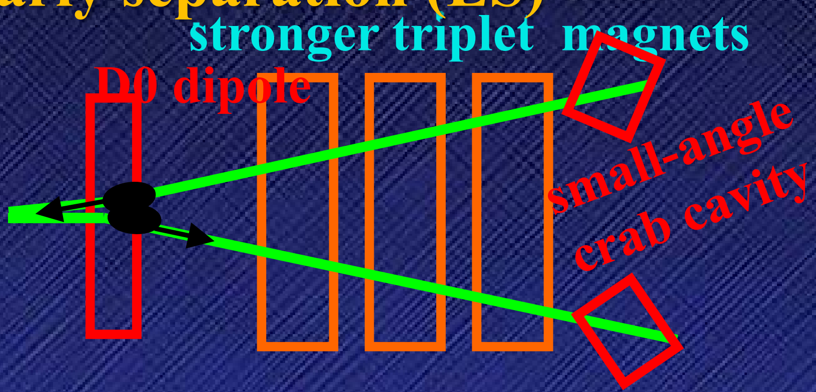
Schedule NOT formally approved by Atlas, CMS and LHCC



"phase-2" IR layouts

early separation (ES)

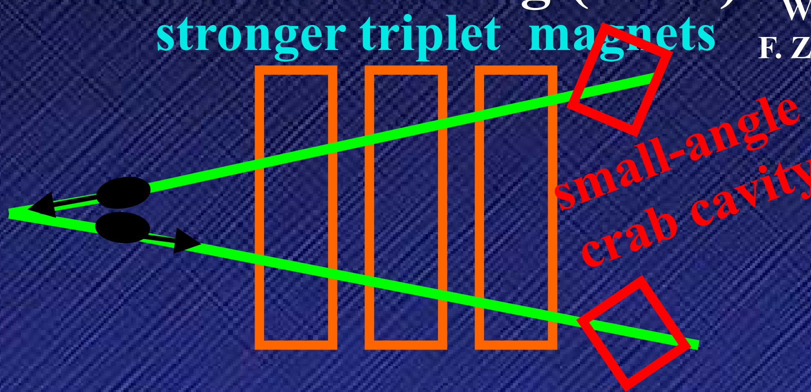
J.-P. Koutchouk



- early-separation dipoles in side detectors , crab cavities
  → hardware inside ATLAS & CMS detectors,
  first hadron crab cavities; off-δ β

full crab crossing (FCC)

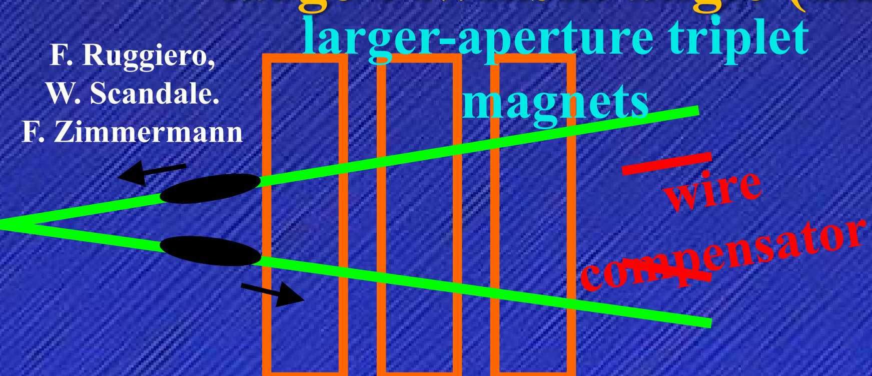
L. Evans,
W. Scandale,
F. Zimmermann



- crab cavities with 60% higher voltage
  → first hadron crab cavities, off-δ β-beat

large Piwinski angle (LPA)

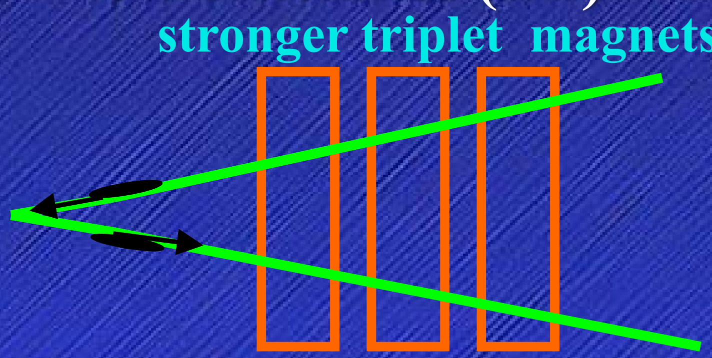
F. Ruggiero,
W. Scandale.
F. Zimmermann



- long-range beam-beam wire compensation
  → novel operating regime for hadron colliders,
  beam generation

low emittance (LE)

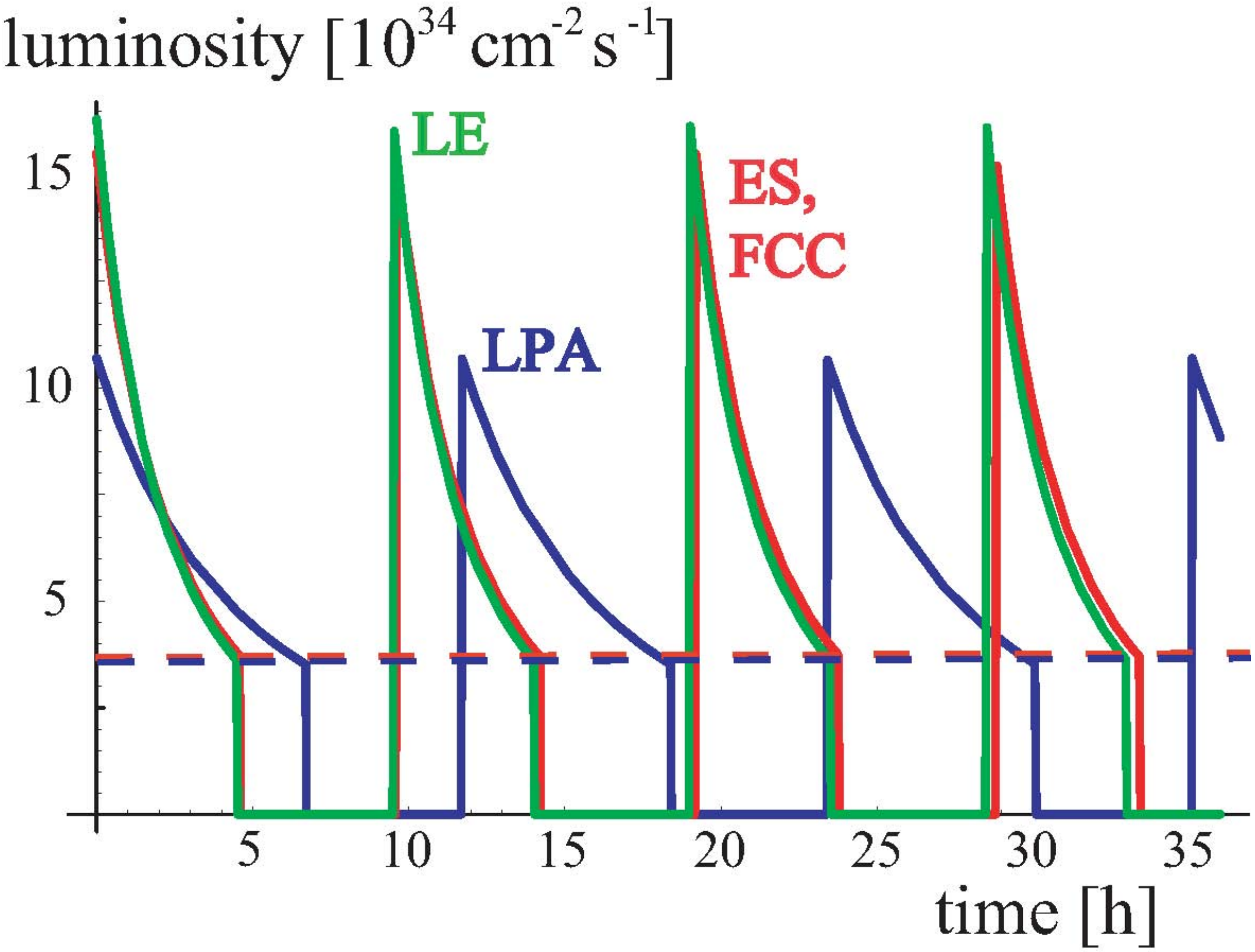
R. Garoby



- smaller transverse emittance
  → constraint on new injectors, off-δ β-beat

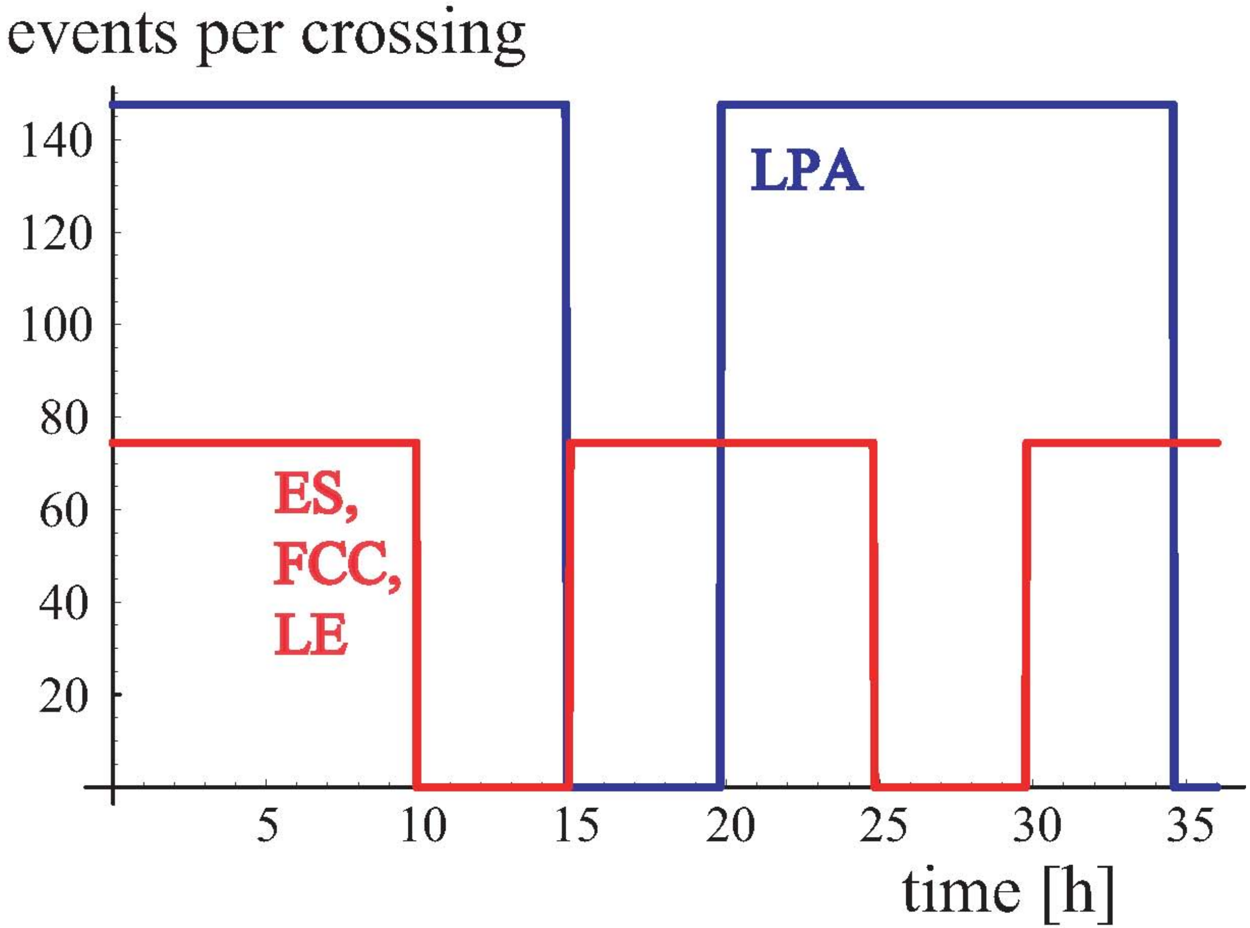
Basic luminosity during phase II running

- Experiments: causing pile-up problem (up to 400 interactions/crossing)



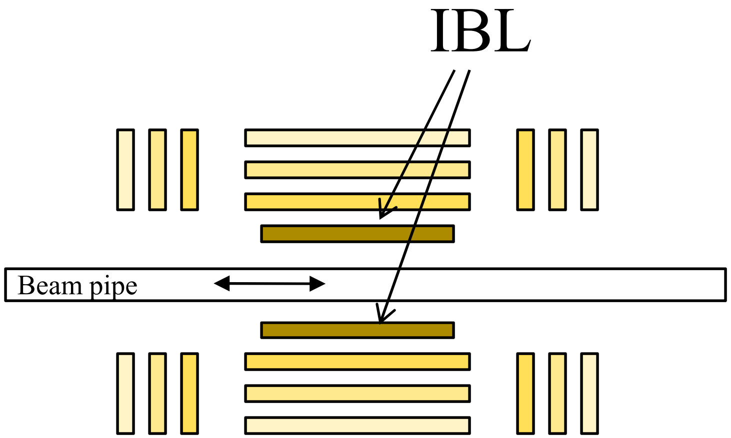
Plan solving pile-up problem by luminosity levelling

- By dynamic tuning of β (beam size function), θ (collision angle), crab voltage (ES or FCC) or bunch length



LHC phase I upgrade

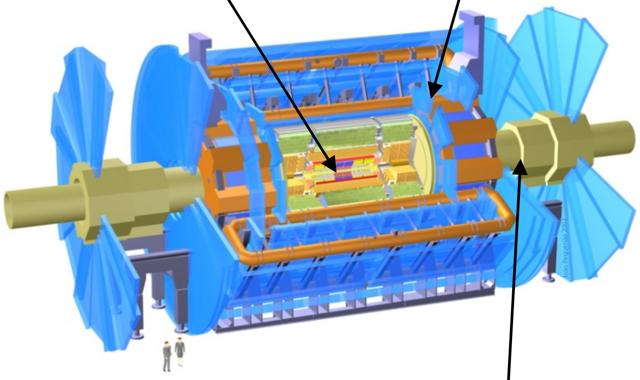
- Proceed to ~ **700 fb-1** of recorded data
- Still using the existing Inner Detector
- Adding IBL (insertable B-layer) inside existing Atlas pixel tracker
  - Present B-layer fails at $L > 10^{34}$ cm^{-2} s^{-1} (readout occupancy)
  - New beam pipe (28 mm) required



- Limited performance of TRT at 3* 10^{34} cm^{-2} s^{-1}
  - Occupancies from 10 – 40% to 30 -70 % (barrel) and 40% (endcap)
  - But still enhancing tracking

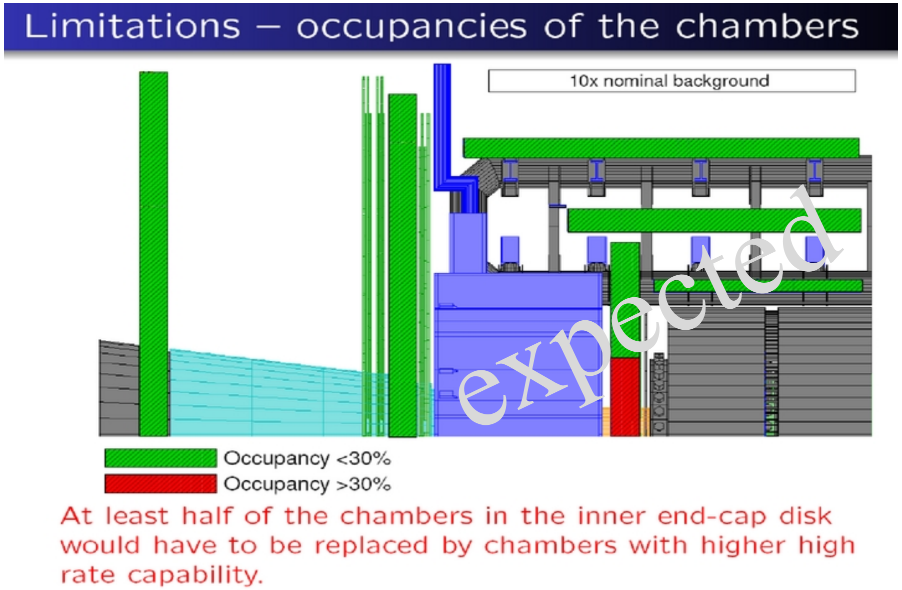
LHC phase II upgrade

- Proceed to **additional** ~ **3000 fb-1** of recorded and ***analyzable*** data
  - => actual detector dose will be higher
- Modifying cavities
- $L \Rightarrow 10^{35}$ cm^{-2} s^{-1}
- Beam crossings 4 → 2 (only CMS and ATLAS)
- **Complete replacement inner detector (ID)**
- Upgrading muon system and calorimetry
  - Scope presently unknown
- Trigger upgrade



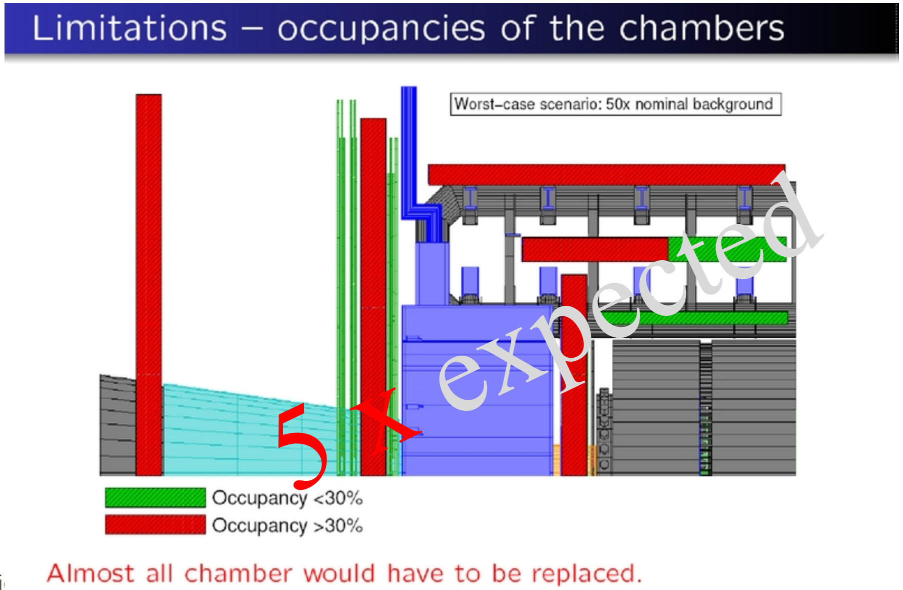
Depending on cavern background

Scope of the ATLAS Muon Chamber Replacement for phase II

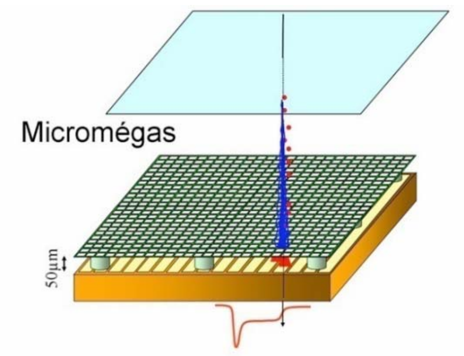


- Depending on cavern background, either minimal (nominal) or very large fraction (5 x nominal) of Atlas muon system needs replacing

- New detector technologies may be used
  - large area woven Micromegas

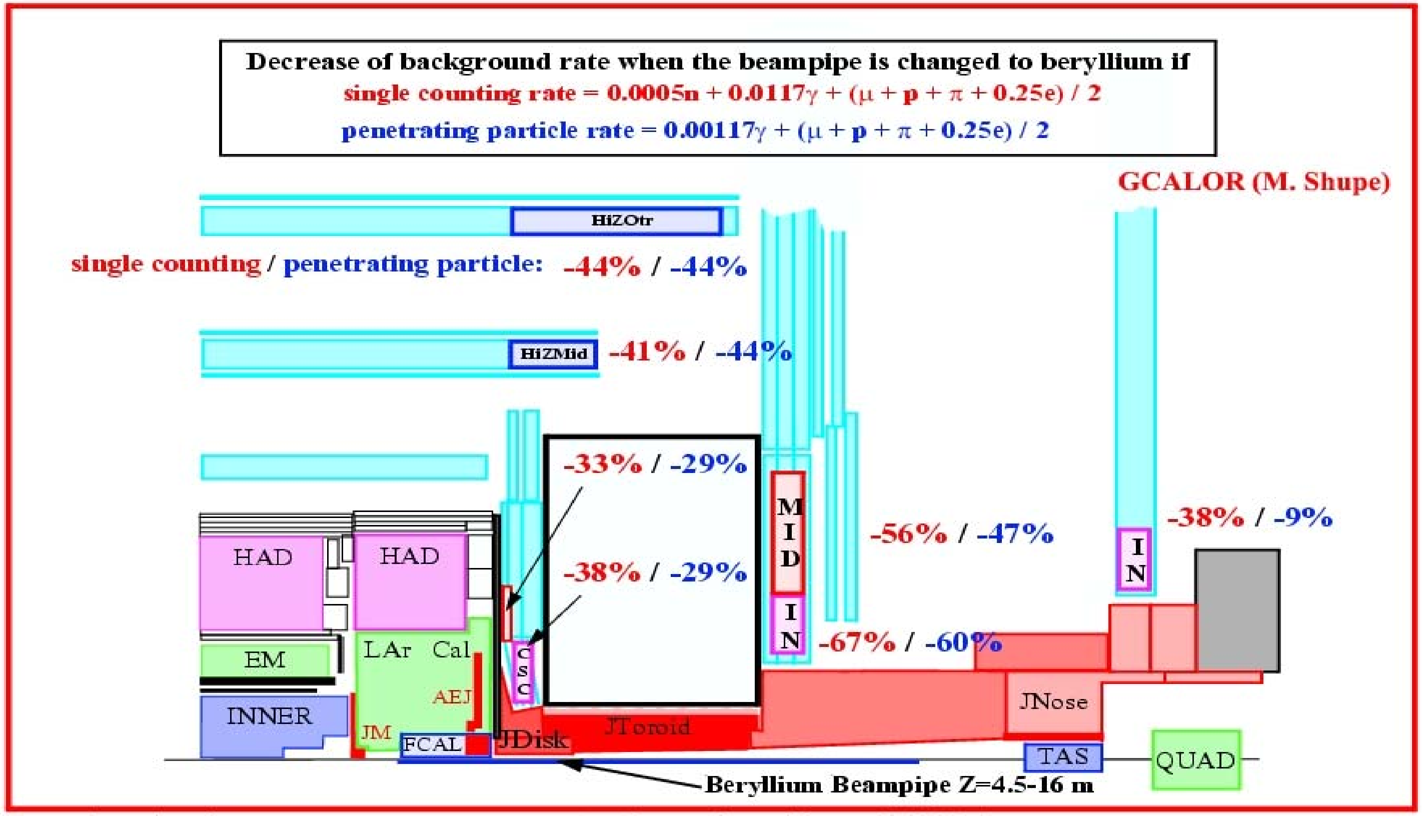


Ref: J. Wotschack, 2nd RD51 Coll. Meeting; See this conference



A beryllium beampipe

A beryllium beampipe is also the only way of significantly reducing the background in the muon spectrometer.

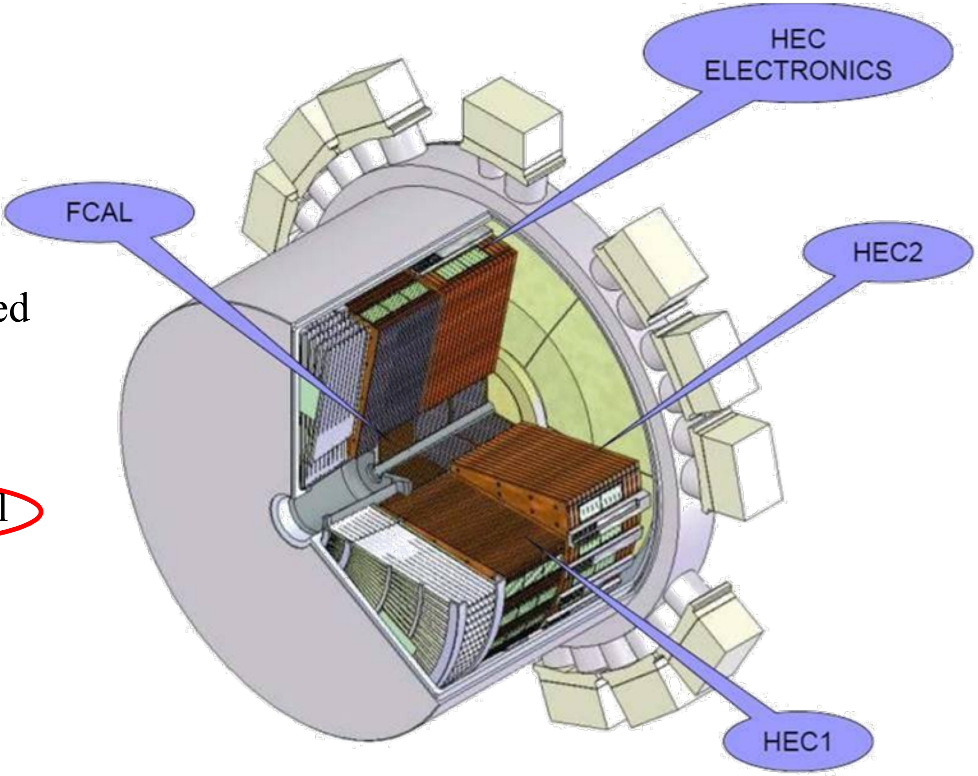


V. Hedberg - CERN / Lund   ATLAS Upgrade Workshop - 01.10.2006   7

- SS or Al --> Be in ECAL and EC-toroid region
- Much cheaper than building new chambers

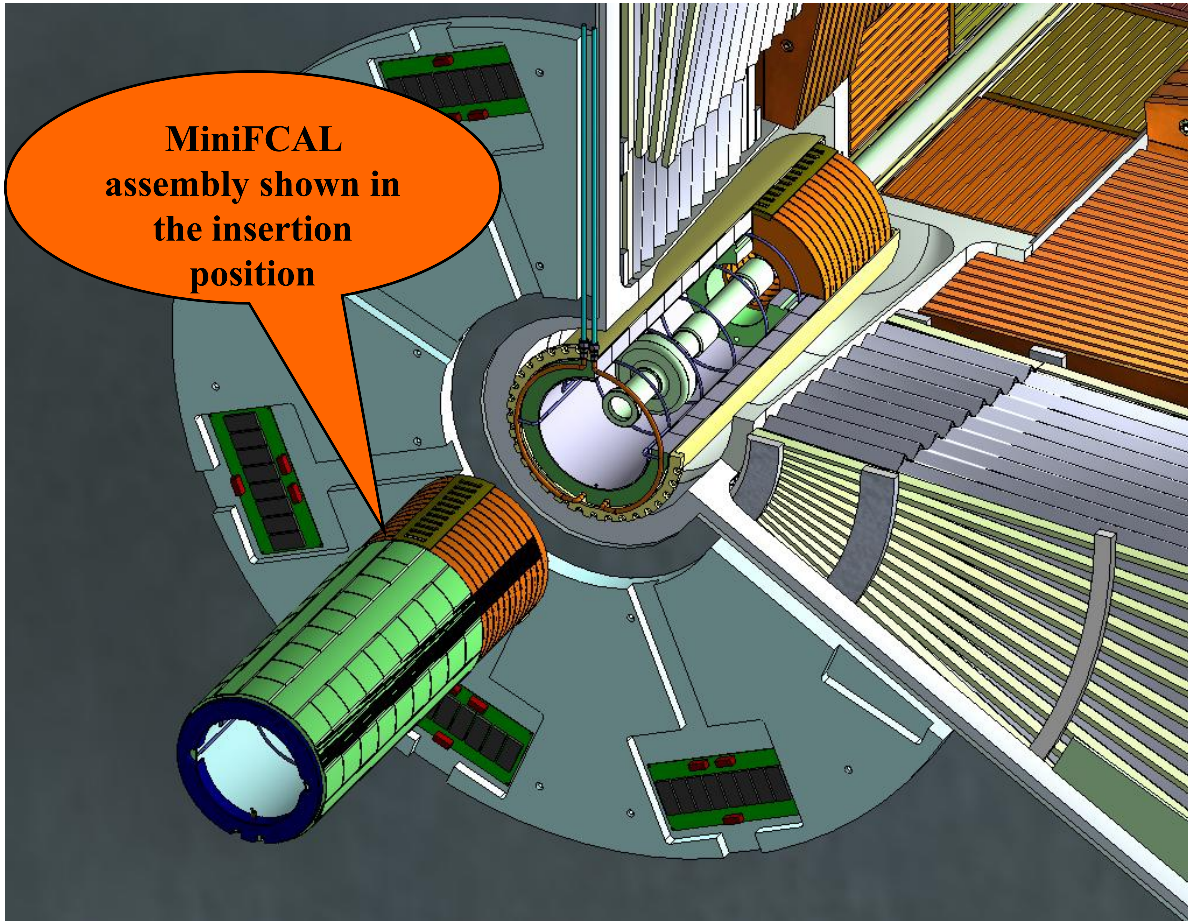
Forward LAr calorimeter upgrade for phase II

- **Option 1** : replace both
  - HEC cold electronics
  - Cold FCal
- **Option 2**: replace only cold FCAL
  - large cold cover needs to be removed
- **Option 3**: do not remove anything
  - Add Mini-FCal in front of cold Fcal



Option 3: radiation absorbing by MINICAL

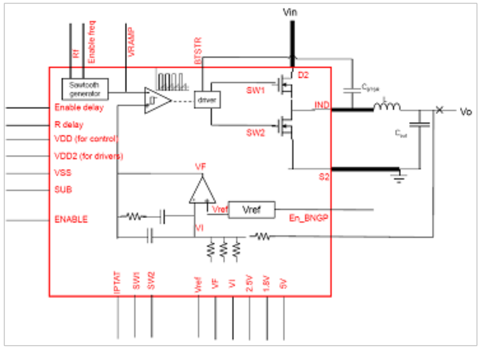
- MINICAL either copper or fromTungsten/diamond sandwiches
- Radiation dose goes to $2*10^{18}$ n/cm^2 (Shupe)



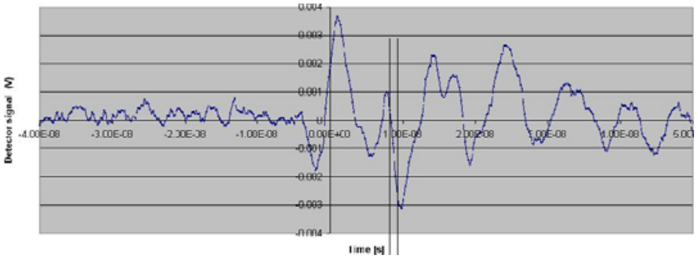
Roy Langstaff, LAr sLHC Detector Meeting, May 25, 2009

Services → developing new technologies for phase II

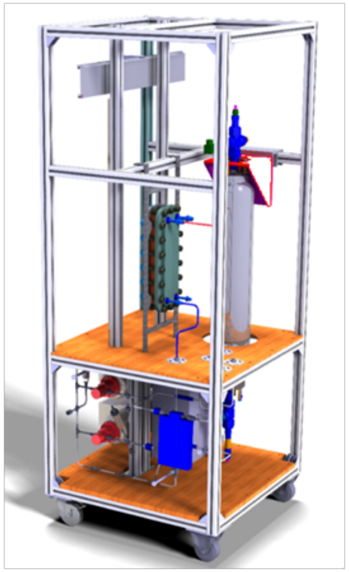
- Powering



- Optical links



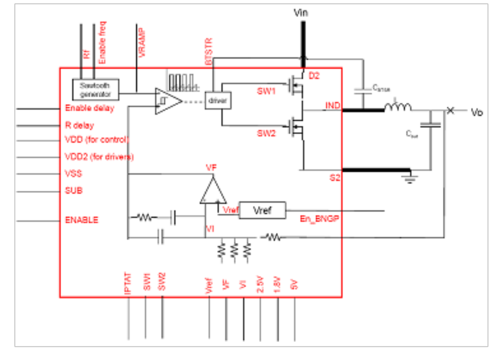
- Cooling



Powering technologies for phase II

Motivation

- Upgraded ID will have much more detector modules
- New electronics (130 nm or smaller) have low supply voltage (~2V)
- No substantial increase of cabling foreseen
- Present SCT: ~ half of electrical power goes into cables



Integrated DC-DC converter
F.Faccio, Atlas Upgrade Week, Feb. 24, 2009

Serial powering

- Local voltage regulation for each detector module

But:

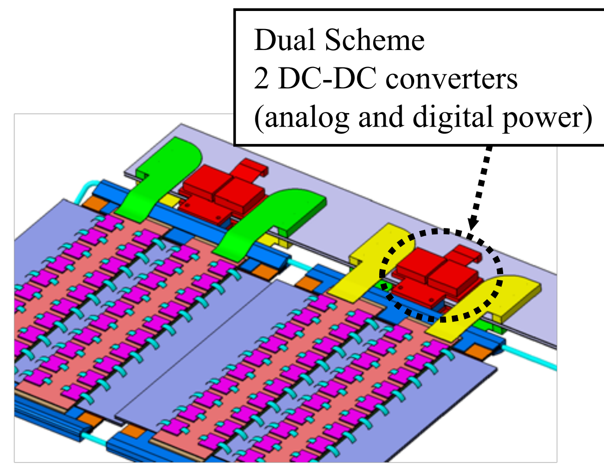
- Problem: no well defined GND potential on modules

Parallel powering using DC-DC converters

- Input 12 – 20V, regulation to ~ 2V
- All detector GNDs may be linked together

But:

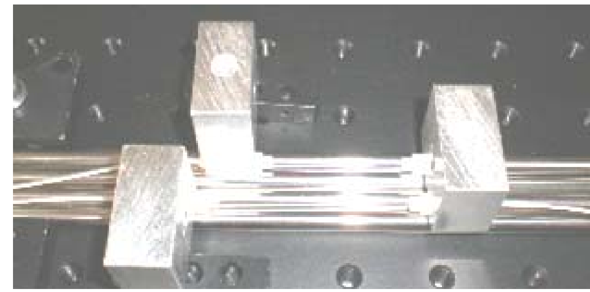
- Risk on switching noise (ironless inductors)



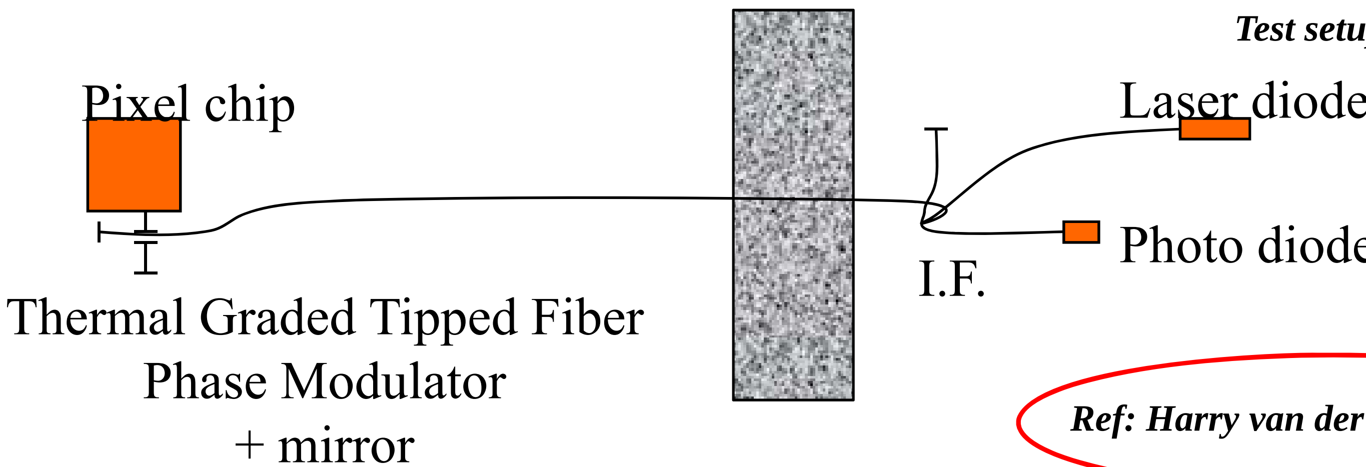
Integration in ATLAS SCT module design
From D.Ferrere
University of Geneva

New optical link technology => Iflink

- Present VCSEL technology not sufficient rad hard (1.5 10^{15} cm^{-2} n_{eq}) for B-layer
- Alternative => **Iflink**
  - Using Pockels effect: change of ε_r by transverse E field
  - Thermally poled electro-optic active fibre (quartz)
  - => possibly sufficiently rad-hard for B-layer
    - Low modulator mass
  - TU-Delft (Neth.) and ACREO (Sweden) involved

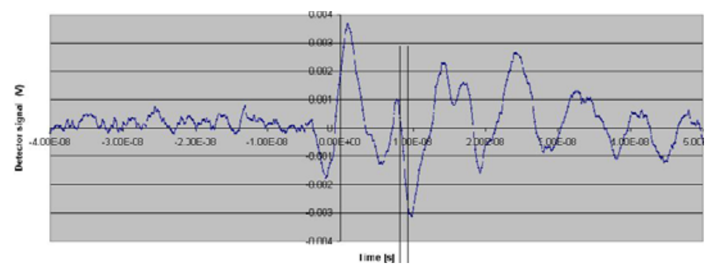


Test setup modulator



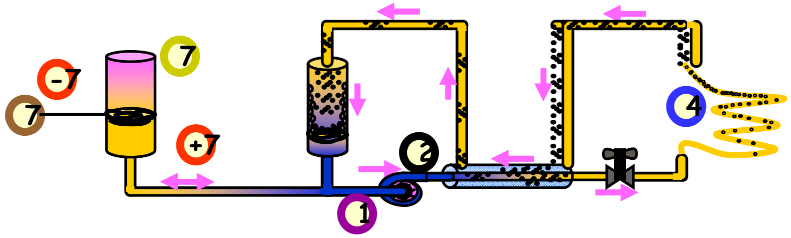
Ref: Harry van der Graaf, Nikhef

Response from a step function
=> 1 ns risetime

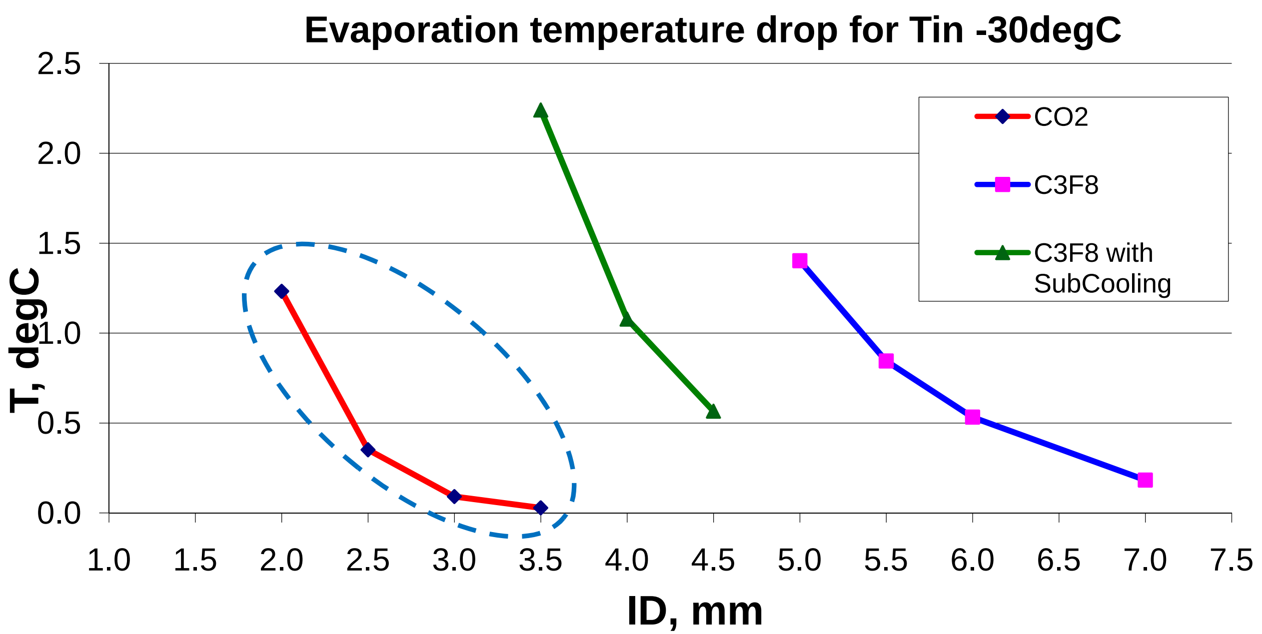


Cooling

- Present SCT and pixel tracker: C_3F_8
- Upgrade possibly CO_2
  - Cheap
  - Environmental neutral
  - Lower temperatures possible (-30 ºC pipe temperature, option - 40 ºC
  - Thinner pipe diameter possible (4 → 2 mm ID), better flexibility



B. Verlaat, Atlas upgrade week, Feb. 25, 2009



M. Battistin, Atlas upgrade week, Feb. 25, 2009

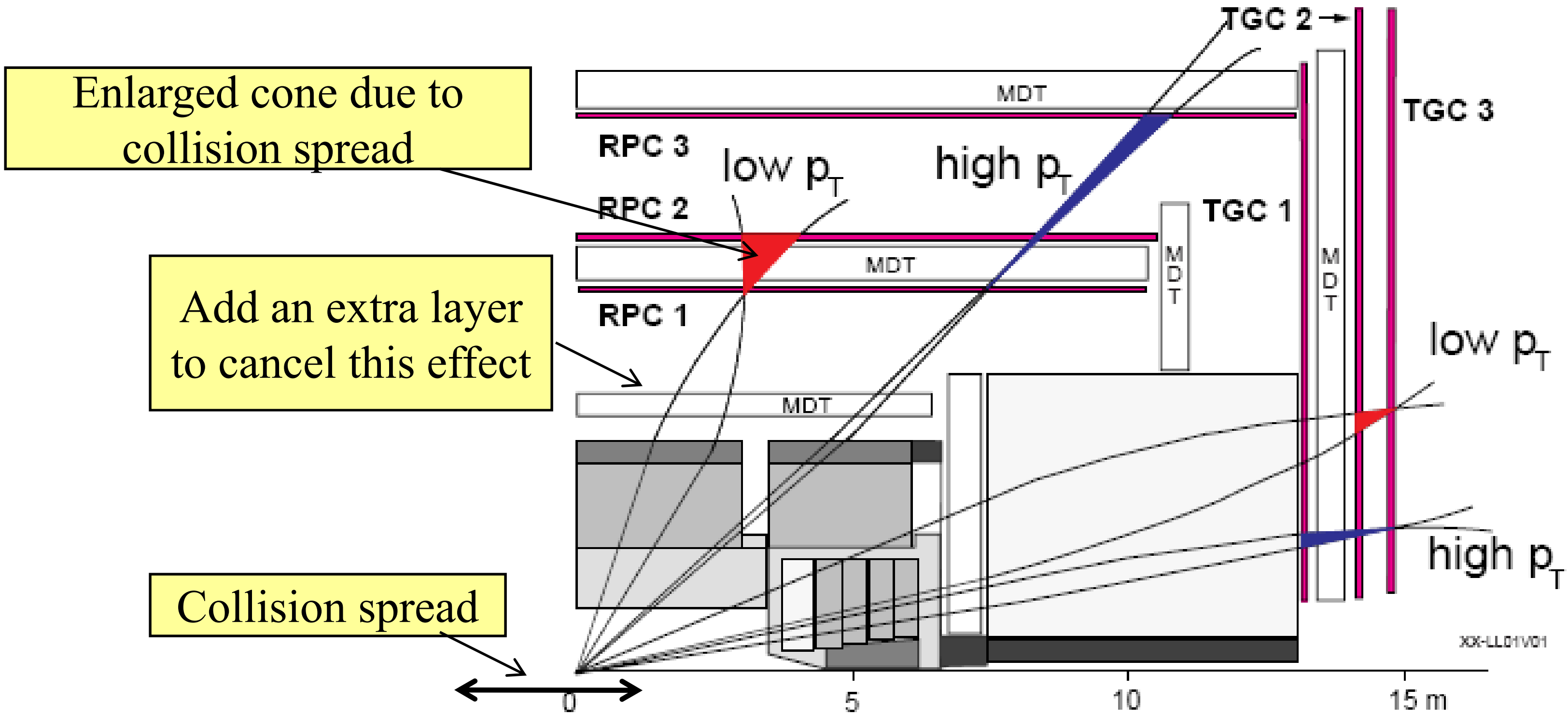
Trigger and DAQ after phase II

- L-1 exceeding 100 kHz at 10^{35} cm^{-2} ms^{-1}
- Muon trigger needs improvement

- **Option 1**
  - Add forward detectors (TGC or MPGD)
  - Add RPC
  - Cutting low integral-B dl regions
    - Tracks passing both barrel and endcap (opposite) toroidal fields
    - => no proper momentum measurement
  - Improvement calorimeter trigger
    - Use full granularity
- **Option 2**
  - Combine subtriggers at level-1
    - => check for isolated muon => far from any calorimeter trigger?
- **Option 3**
  - Create track trigger from ID
    - => very challenging
    - GridPix trigger (see Anatoli Romaniouk, next talk)

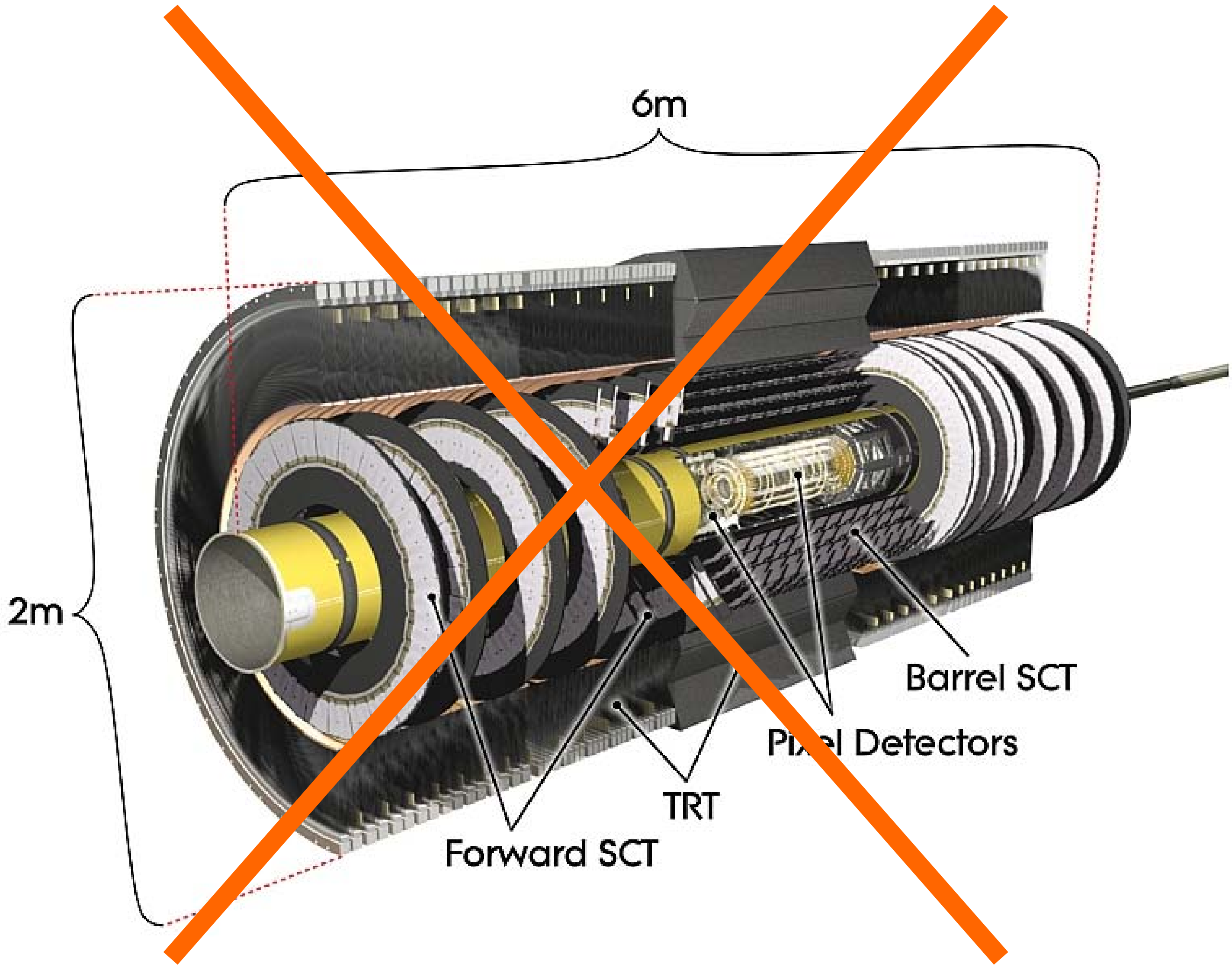
Improving sharpness of muon trigger

- RPCs are used for fast trigger
- Adding additional trigger chambers (RPC) to cancel the momentum error by collision spread on low P_T tracks



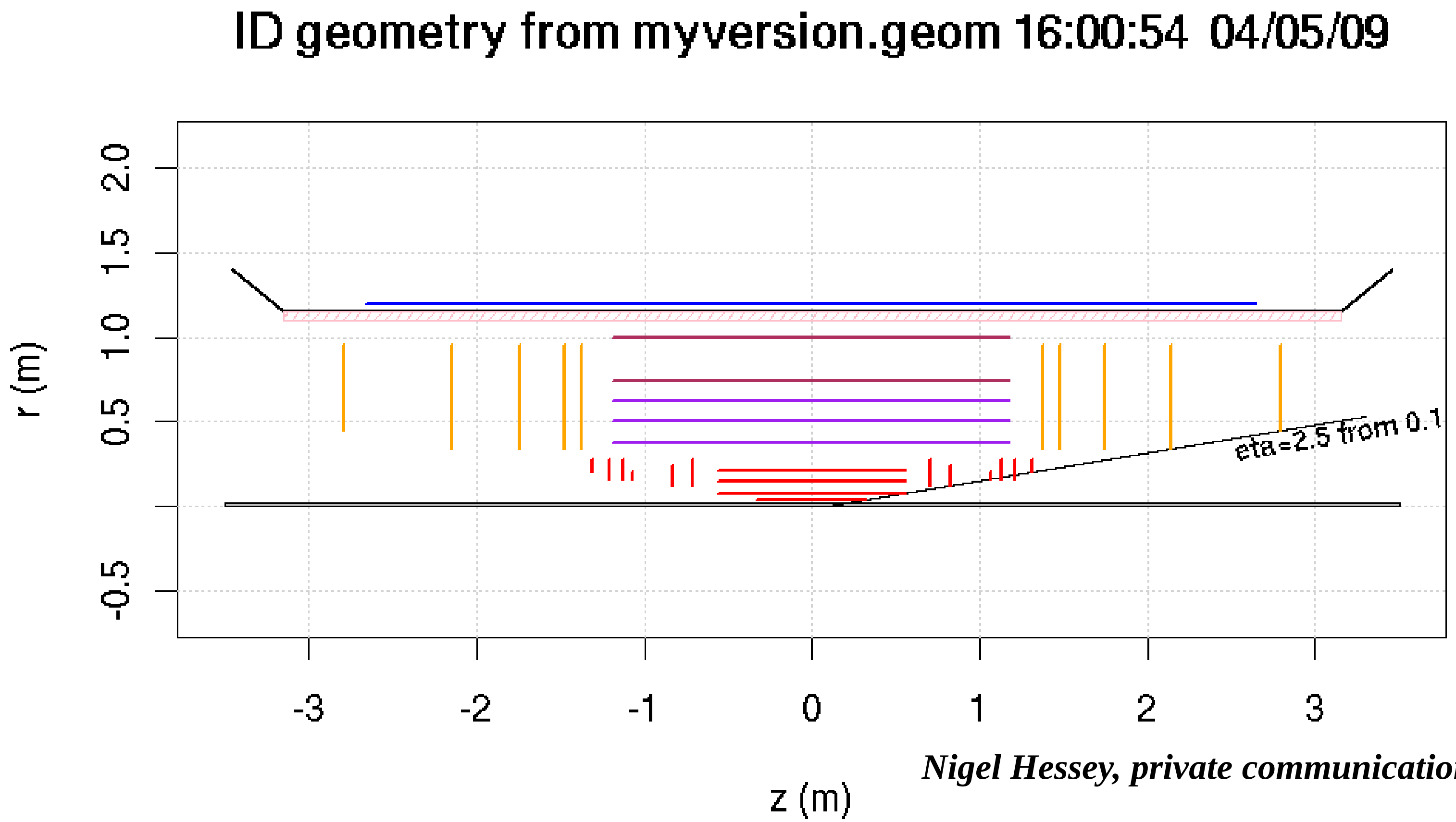
George Mikenberg, Atlas Upgrade Week, Feb. 26,2009

Complete replacement of the Inner Detector in phase II



Inner detector layout in phase II

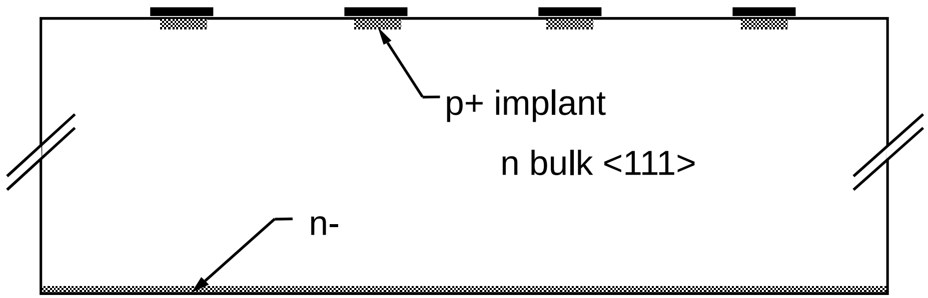
- Baseline layout
  - 2 long strip layers
  - 3 short strip layers
  - 3 pixel layers
  - 1 B-layer (pixel layer 0)



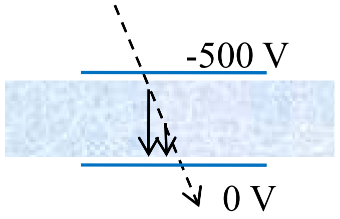
Nigel Hessey, private communication, June 3, 2009

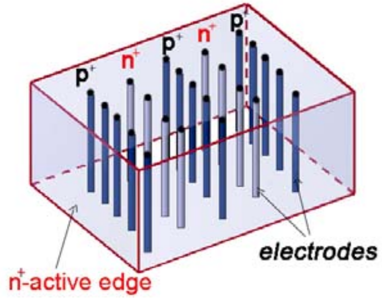
Which detector technologies can be used for upgraded Inner Detector in phase II?

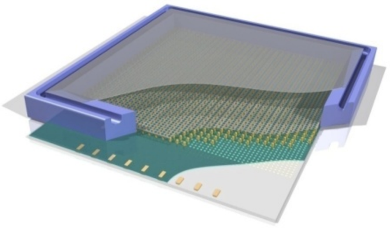
- Baseline: planar silicon



- Alternatives
  - 3D silicon
  - Diamond
  - Gossip (gaseous pixel detector)



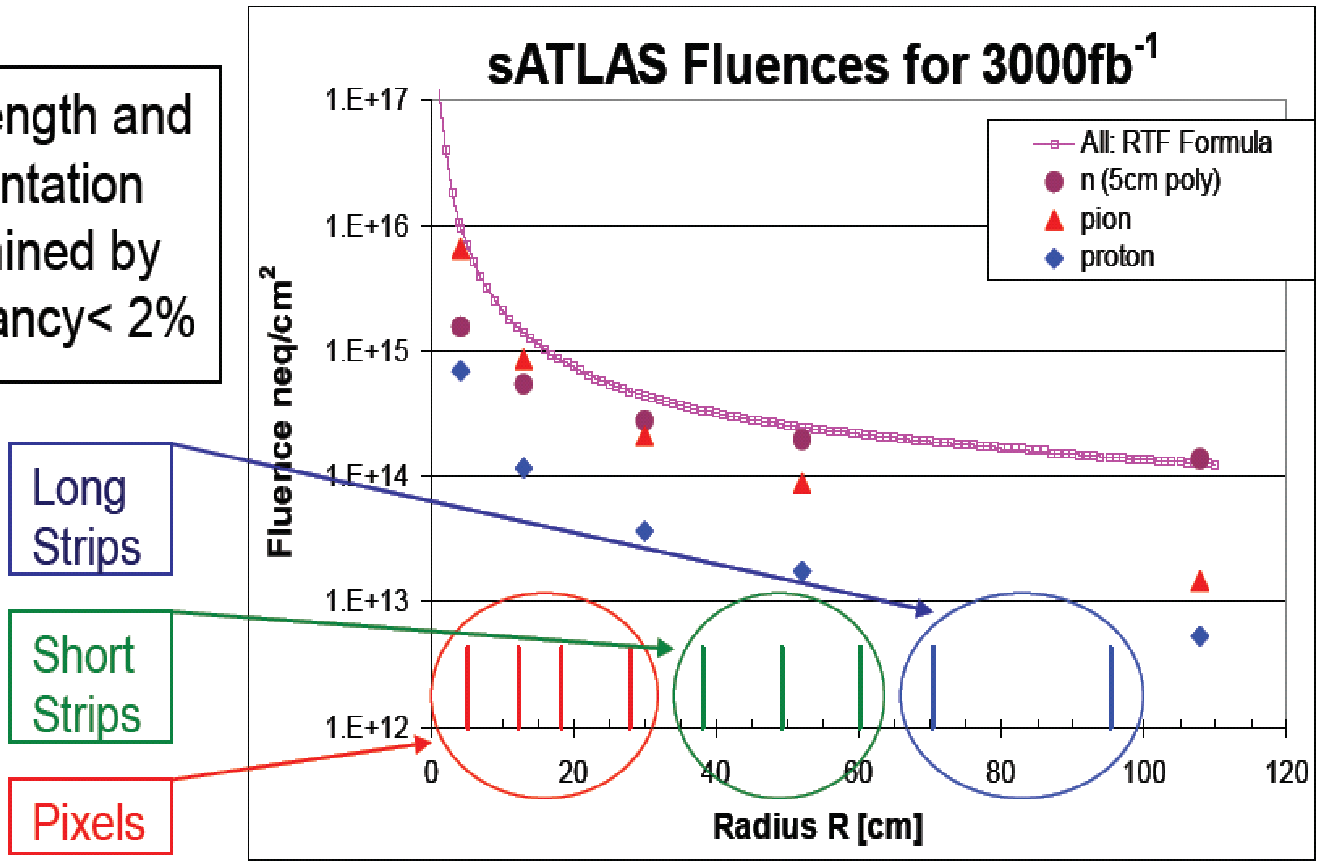




Fluences for subdetectors after 3000 fb^{-1} (1 MeV n_{eq} cm^{-2})

- Long strips: ~ 1.5 $*10^{14}$
- Short strips: 2 – 3 $*10^{14}$
- Pixels: 0.6 – 8 $*10^{15}$ **(omitting B-layer)**

Strip length and segmentation determined by occupancy< 2%



Mix of neutrons, protons, pions depending on radius R

Long and short strips damage largely due to neutrons

Pixels damage due to neutrons and pions

ATLAS Radiation Taskforce http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/RADIATION/RadiationTF_document.html

Fluence for the B-layer at sLHC in phase II

- R = 37 mm
- Dose
  - At b-layer radiative dose is dominated by direct tracks
  - Assume 3000 fb^{-1} data * safety factor 2 * 79 mb pp Xsec * 6.3 tracks/η /interaction
  - → **$3*10^{17}$ tracks/η** (mostly pions)#
  - At R = 37 mm, 1 cm is 0.269 units of η and 0.268 units of ϕ out of 2π
  - → at R = 37 mm we get **$3.4*10^{16}$ charged particles/cm^2**
    - (Damage factor ~0.6 for pions → **$2.0*10^{16}$ n_{eq}/cm^2** relevant for Si)#
- Rate
  - **0.9 GHz/cm^2 for 25ns sLHC**

Corresponds to 9.5 * 10^6 Gy (950 Mrad)

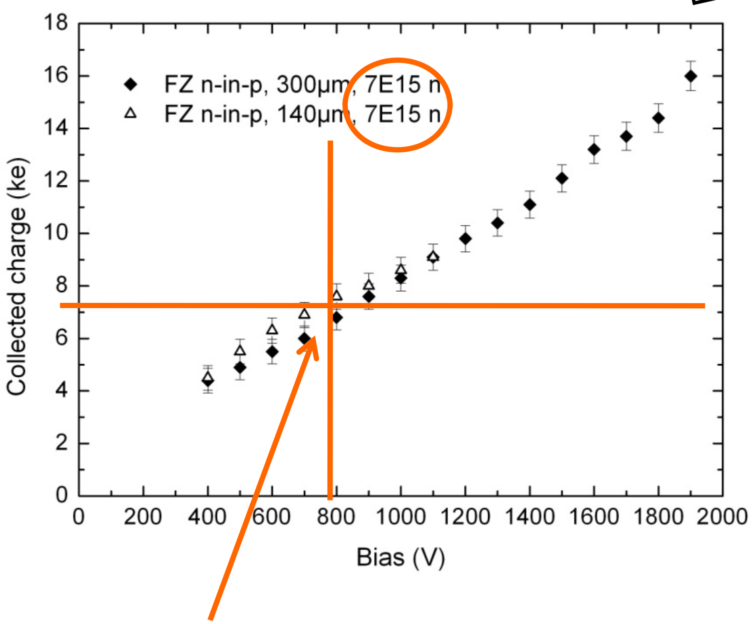
Data from Atlas experts (Craig Buttar, Ian Dawson and Nigel Hessey)

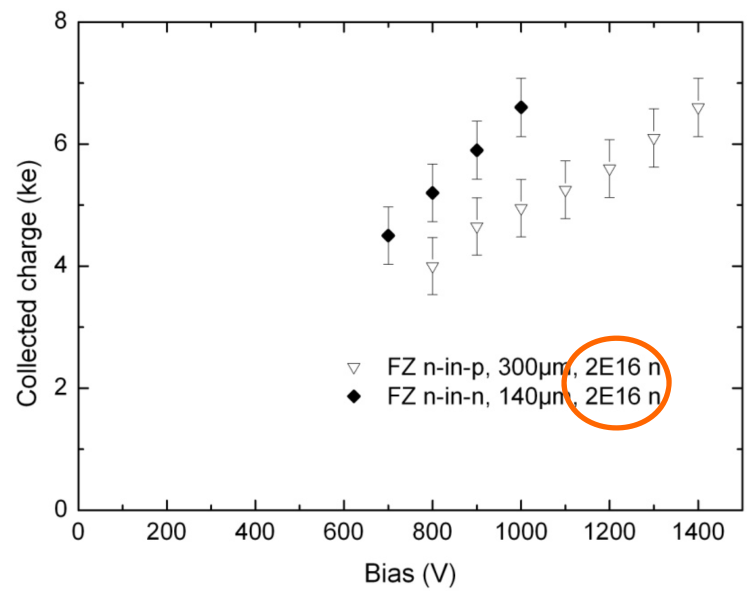
Progress in planar silicon

- Recent irradiation data (Trento workshop, Atlas Upgrade week Feb. 2009)
  - Ageing **less** than proportional
- Determine working point based on
  - Charge signal
  - Bias current
    - => heat, shot noise

Operation at -25 ºC!

Ref: sLHC B-layer => dose 2.0 *10^{16} n_{eq}/cm^2





Possible working point
800 V => 7 ke-

Plots from G. Casse, Atlas Upgrade Week, Feb. 25, 2009

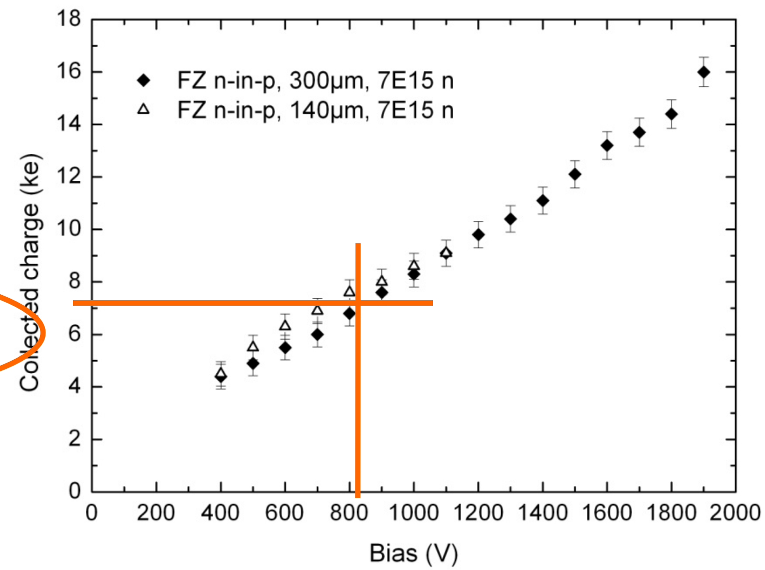
Required charge signal

- 800 V working point using FE-I4 pixel chip @ **7 * 10^{15} n_{eq}/cm^2**
  - => ~ 150 ENC (110 µA/cm^2) shot noise $\sigma_i = \sqrt{2 q I \Delta f}$
  - => ~ 500 ENC total noise
  - => bare threshold 2.5 ke^-
  - Overdrive ~ 1.25 ke^-
  - Charge sharing: x 2

Required signal for good operation of detector:
(bare threshold + overdrive) x 2

- **=> ~ 7.5 ke^- signal required**
- Available **7 ke^-** after 7 * 10^{15} n_{eq}/cm^2

- → 7 * 10^{15} n_{eq}/cm^2 is doable, but at the limit



Plot from G. Casse, Atlas Upgrade Week, Feb. 25, 2009

Conclusions using planar silicon for phase II

- Maximum permissible dose 7 $*10^{15}$ n_{eq}/cm^2
- => OK for
  - Long strips (~ 1.5 $*10^{14}$ cm^{-2})
  - Short strips (2 – 3 $*10^{14}$ cm^{-2})

- At the limit for
  - Pixel layers (0.6 – 8 $*10^{15}$ cm^{-2})
  - Dangerous for pixel layer 1

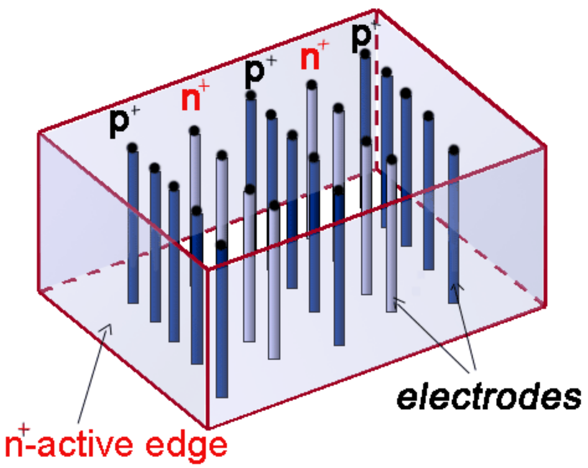
- Complication: operation at -25 ºC

- => other technology required for
  - B-layer (2 $*10^{16}$ n_{eq}/cm^2)

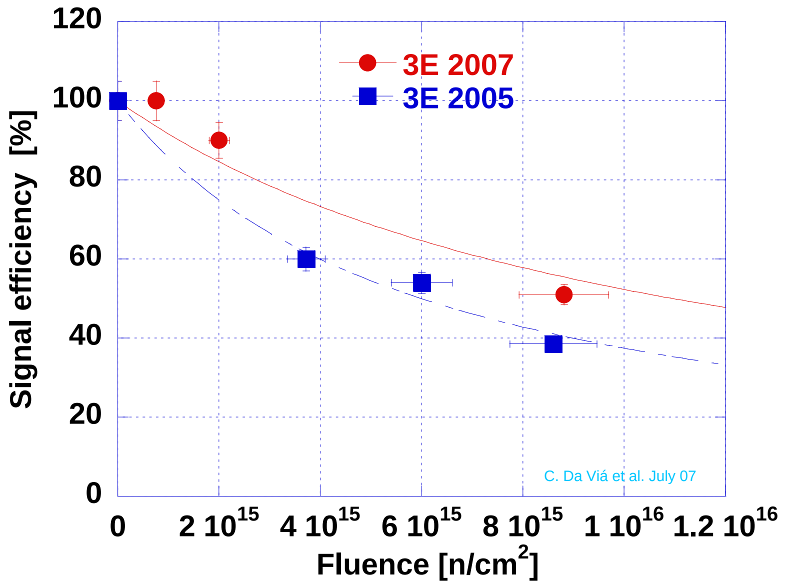
- => or replacing B-layer 3-5 x during sLHC lifetime

3D silicon

- 3D silicon
  - Reducing path in the silicon bulk by creating n^+ and p^+ channels
    - Low bias voltage, low emitted heat level
  - Edgeless sensor
  - Safe operation until ~ $10^{16}\ n_{eq}/cm^2$
  - => OK for inner pixel layer
  - => problematic for B-layer
  - Operation at -10 ºC



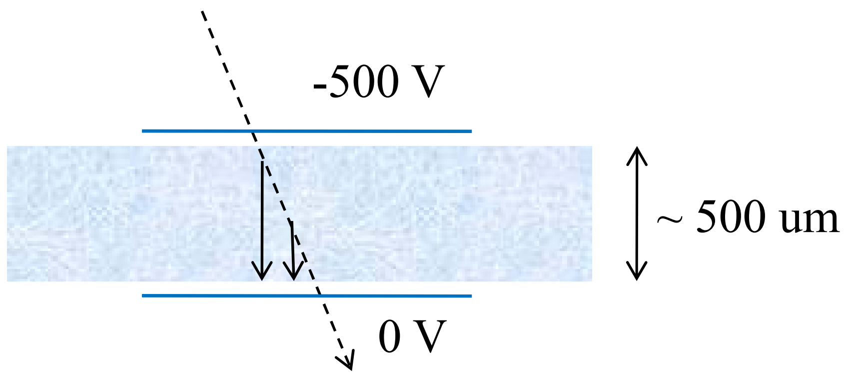
- **But**
  - A bit less performance
    - Efficiency of perpendicular tracks
  - Production problems not well solved
  - A bit long charge collection time (20 – 35 ns)

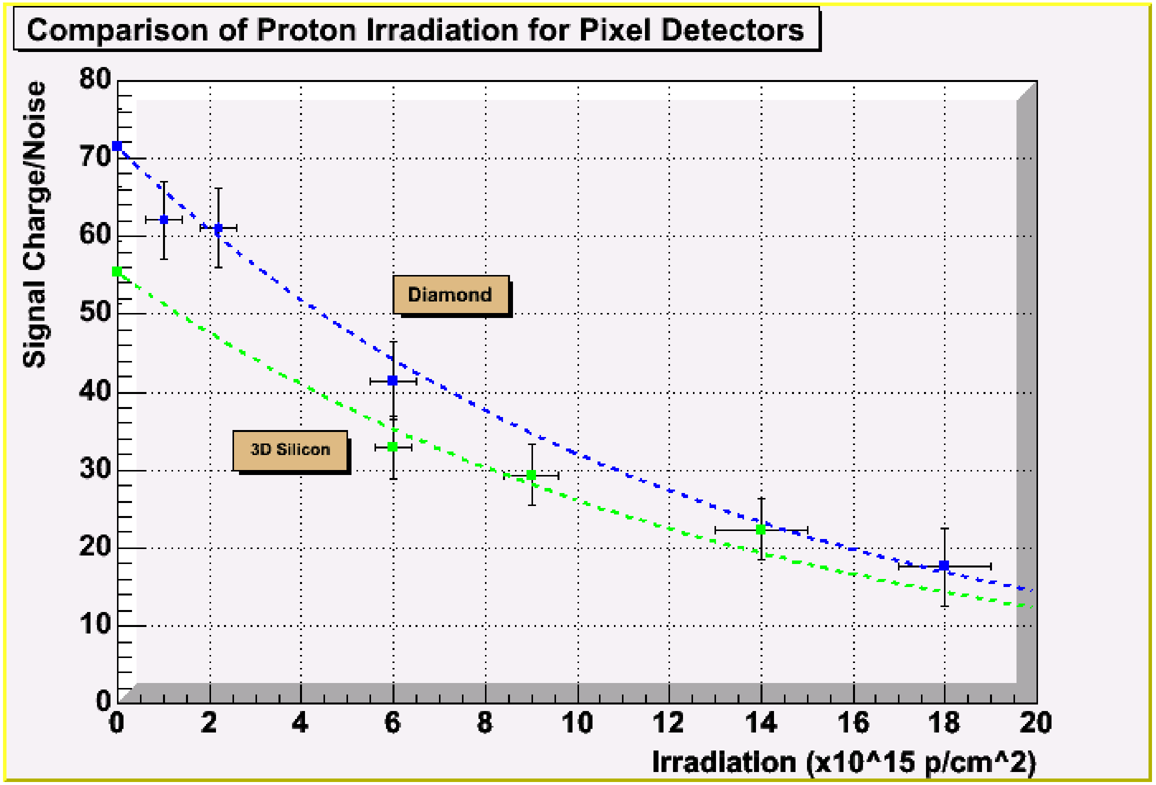


Cinzia da Via, Atlas Upgrade Week, Feb. 23, 2009

Diamond

- **Pro**
  - Presently charge signal > 10ke⁻
  - Low capacity ($\varepsilon_R = 5.7$)
  - No bias current (10 pA region)
  - Simple operation at any temperature
  - Simple processing
  - Radiation tolerance comparable to 3D silicon

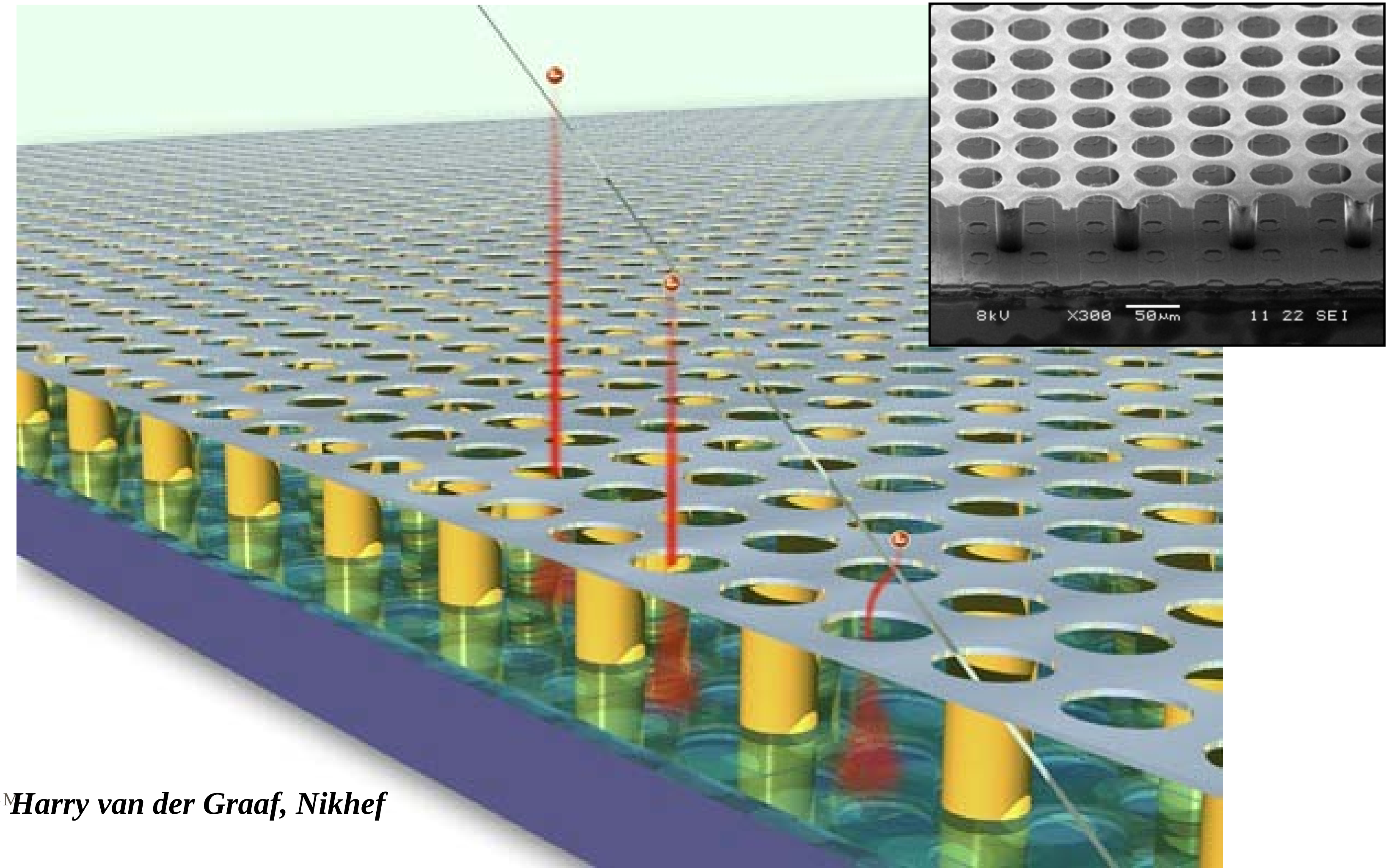




- **But**
  - Polycrystalline CVD diamond: less good position resolution (~ 14 um)
  - Single crystal CVD diamond OK, but hard to produce

Gossip

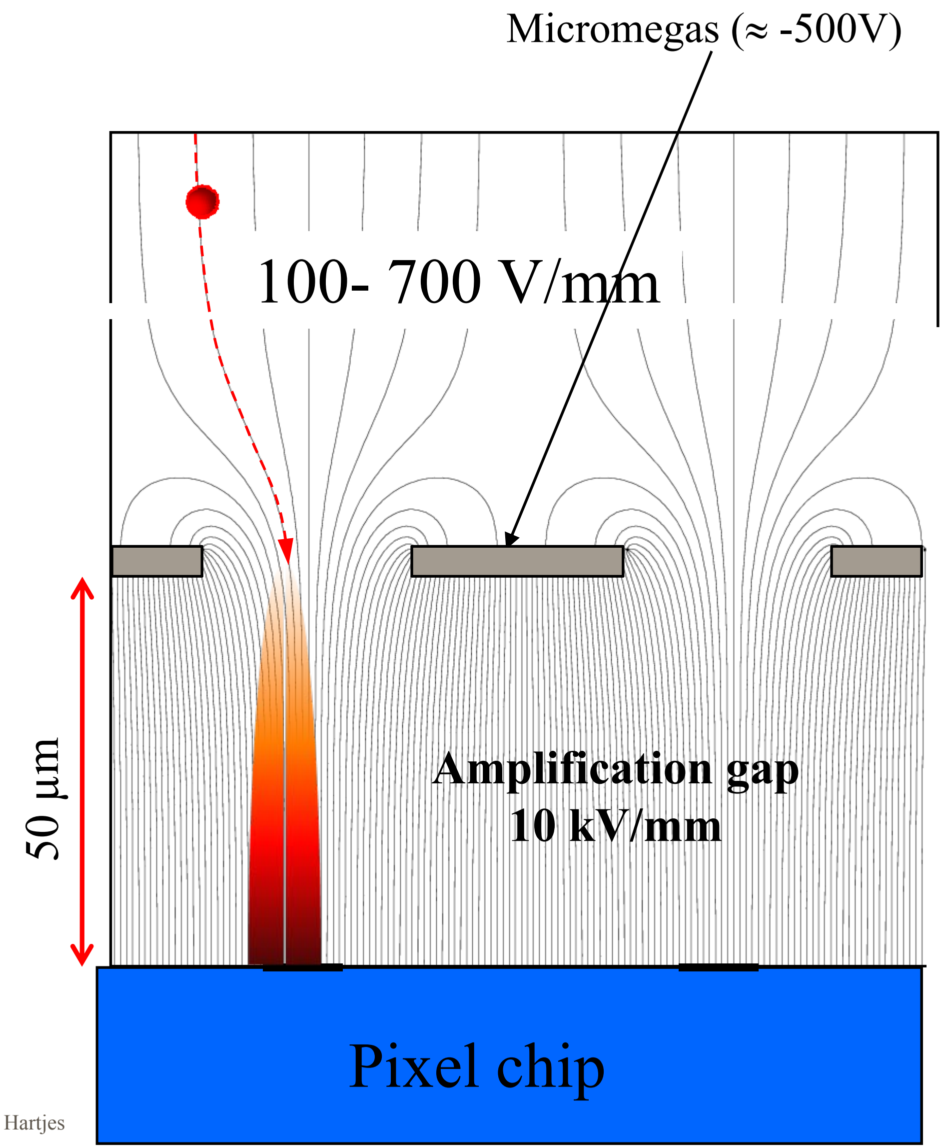
- Gaseous pixel detector
  - Narrow drift gap (~ 1 mm)
  - Electron from traversing particle drifts towards grid and is focused into one of the holes
  - Thereafter a gas avalanche is induced ending at the anode pad of the pixel chip



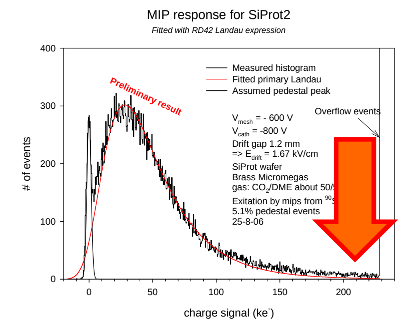
Ref: Harry van der Graaf, Nikhef

Field configuration of GOSSIP

- Comparatively low drift field (100 – 700 V/mm)
- High amplification field (~ 10 kV/mm) to induce gas avalanche
- Micromegas holes centred on pads pixel chip
- Avalanche broadened by diffusion to 15 – 20 µm



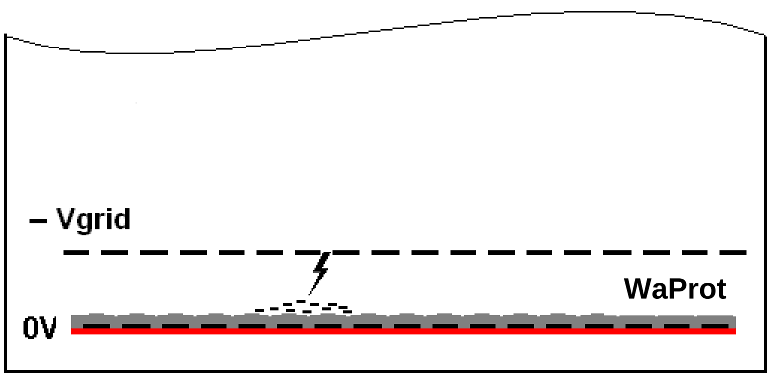
Spark protection

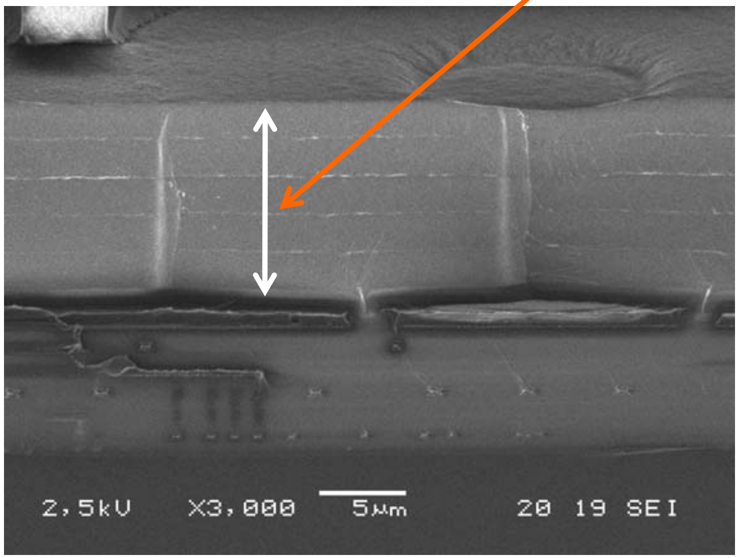


- Always needed for gaseous detectors
  - Spark induced by dense ionisation cluster from the tail of the Landau
  - Unprotected pixel chip rapidly killed by discharges

5 layers of 1.4 μm Si_3N_4

- WaProt: 7μm thick layer of **Si_3N_4** on anode pads of pixel chip
  - Normal operation: avalanche charge capacitively coupled to input pad
  - At spark: discharge rapidly arrested because of rising voltage drop across the WaProt layer





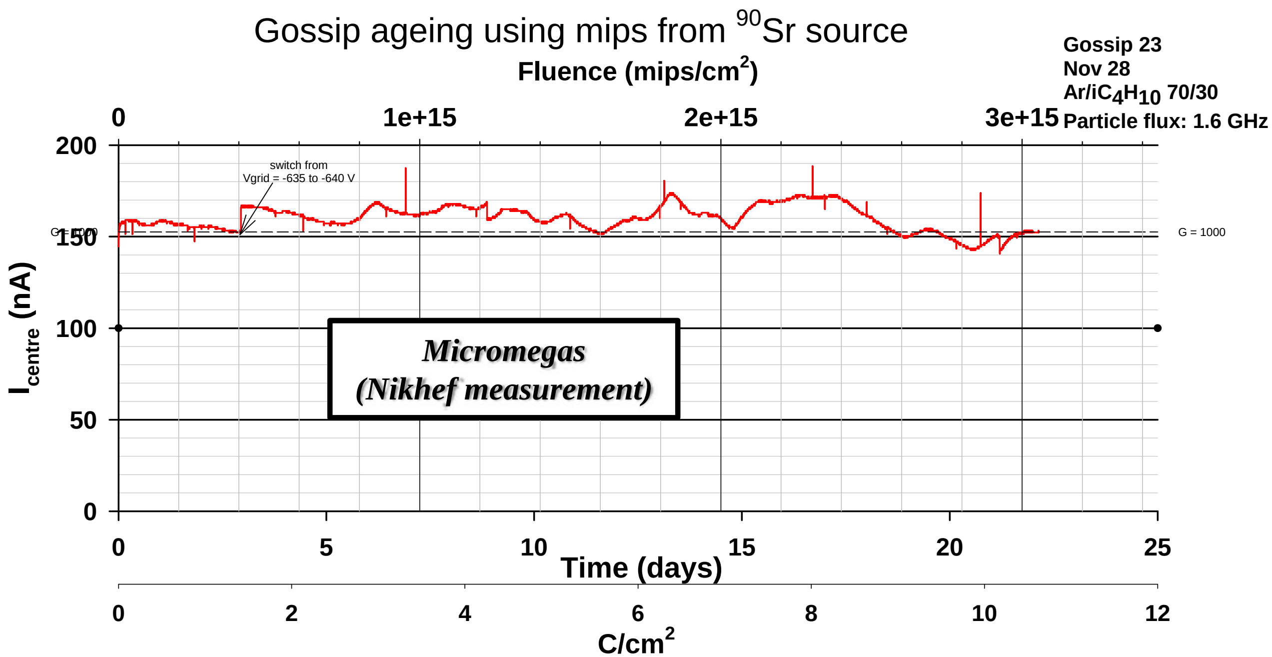
  - Conductivity of WaProt tuned by Si doping
  - For sLHC BL we should not exceed $1.6*10^9$ Ωcm (10 V voltage drop)
  - Has proven to give excellent protection against discharges

Gossip working point for present studies

- **Chamber gas**: DME/CO_2 50/50
  - Low, constant mobility, even at high drift fields
  - → low Lorenz angle (~9º at B = 2 T)
  - High primary ionization (45 clusters/cm)
  - Excellent quencher (UV absorption, preventing sparks)
  - Low diffusion (σ = 100 µm/√cm)
- **Gas gain** 5000
  - → good Z resolution (slew rate)
  - Optimal hit efficiency
  - Gain of 5000 challenging at B-layer (0.9 GHz/cm^2 rate)!!!
- **Drift gap** 1 mm
  - → theoretical hit efficiency 98.9%
  - → minimal ballistic deficit
- **Drift field** 7 kV/cm
  - → good drift velocity, short drift time even for this low mobility gas

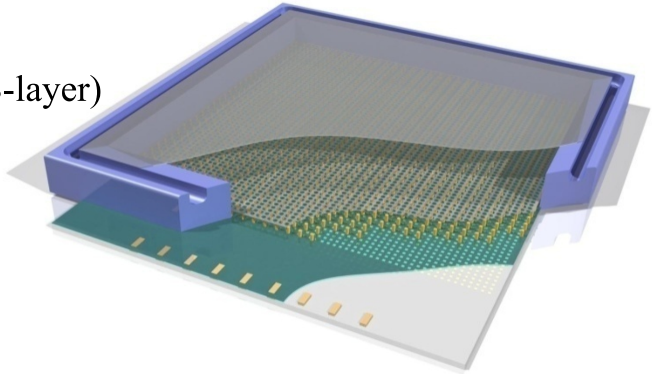
Gossip radiation tolerance

- Dose units: 2 * 10^{16} n_{eq}/cm^2 <=> 3.4 *10^{16} hadrons/cm^2
  - => 342 C/cm^2 using DME/CO_2 50/50 @ G = 5000
  - Corresponds to 2.1 C/cm for 20 µm Ø sense wire



Summarizing Gossip

- Gossip has both very significant advantages and drawbacks compared to solid state detectors
- **Pro**
  - Outlook for extremely high radiation tolerance > 3.4 * 10^{16} hadrons/cm^2
  - Low mass (0.7% including cooling, services and support)
  - No bias current, only signal current
    - ~3.5 μA/cm^2 for 0.9 GHz/cm^2 hadronic flux (sLHC B-layer)
  - Virtually no detector capacity
  - Wide temperature range (room temp. possible)
  - No bump bonding => mass and costs reduction



- **Con**
  - Additional services required (gas pipe, 2nd HV line)
  - Lower position resolution than is possible with solid state detectors
    - **~ 18 – 30 µm @ 0 – 0.15 radian** (from recent simulations)
  - Critical regulation of grid voltage
  - Tendency to sparking => solvable
  - Long charge collection time (20 – 80 ns gas dependent)
  - Risk on accelerated ageing

Comparison of detector technologies for B-layer of sLHC (phase II)

- Assume TimePix-like frontend pixel chip (accurate time info)

technology	Planar silicon	3D silicon	Diamond	Gossip
possible pos resolution (um)	< 10	< 10 ?	~ 14 (polycryst)	~20
resolution for inclined tracks	reasonable	reasonable	reasonable	mediocre
charge collection time (ns)	< 6	20 - 35	2	20 - 80
mass including cooling	pretty high	pretty high	medium	low
life time in SLHC (3000 fb-1)	20 - 50%?	~ 50%	~ 50%	> 100% poss.
production technology	well known	difficult	difficult	much R&D
bias voltage control	easy	easy	easy	critical
ease of operation	reasonable	reasonable	relaxed	critical
cooling	critical	less critical	relaxed	relaxed
additional services	NO	NO	NO	HV + gas
additional DAQ channels	NO	NO	NO	probably
track efficiency	100%	>95%?	98-100%	98%
costs	75 - 300 €/cm2	150 - 300 €/cm2	~ 1000 €/cm2 ?	20-30 €/cm2
size of coll. (ATLAS institutes)	>10	10	6	2
approved R&D?	yes	yes	Yes	near submit

Conclusions on Atlas upgrade activities

- Going to higher luminosity in combination with more advanced triggering enhances LHC's discovery potential
- Limited hardware modifications required for phase I
  - Insertable B-layer
  - Few chambers (RPC, TGC) to be added for improving muon trigger
- Major modifications for phase II
  - Replace present Inner Detector
  - Possible replacement/ modification of muon chambers and FWD calorimetry (MINICAL)
- Research on new technologies for services
  - Powering, cooling, optical links, ...
- Improvements in planar silicon technology
  - => planar silicon may still be used for long and short strips and most of the pixel layers
- Alternative technologies being developed for B-layer in phase II
  - 3D (not full sLHC lifetime)
  - Diamond (not full sLHC lifetime)
  - Gossip (many pros and cons)
- Gossip may also be used for intermediate layers
  - Low radiation length; low costs