Beam Diagnostic Challenges for High Energy Hadron Colliders

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HB2014

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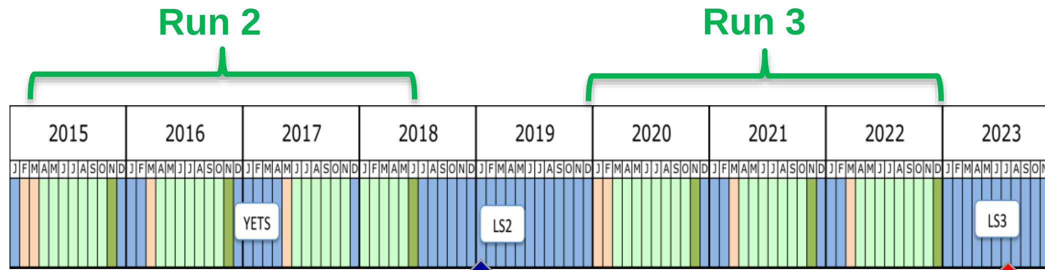
Special thanks to Rhodri Jones, Thibaut Lefevre, Michiko Minty, and Manfred Wendt for their input

High Energy Hadron Colliders – current

		Physics start date	***Max. beam energy [TeV/n]***	***av. Beam current [mA]***	***Peak Luminosity [$cm^{-2}s^{-1}$]***
RHIC Brook-haven 3.8 km circum.	pp polarized	2001	0.255	257	2.1×10^{32}
	AuAu	2000	0.1	145	8.4×10^{27}
	dAu, CuCu, UU, CuAu He^3Au	2002, 2004 2012 2014		up to 159 (depending on ion)	0.9 – 270 $\times 10^{27}$
LHC CERN 26.7 km circum.	pp	2009	3.5 - 4	400	7.7×10^{33}
		2015	6.5 - 7	580	$1 – 2 \times 10^{34}$
	HL-LHC upgrade pp	2025+	7	1200	5×10^{34} (levelled)
	PbPb (pPb in 2012)	2010	1.38	6.8	0.5×10^{27}
		2015	2.76	7.4	1×10^{27} (levelled)
	PbPb high lumi upgrade	2020	2.76	22	up to 7 $\times 10^{27}$

The next 10 Years



6.5 to 7 TeV
Peak luminosity
$1.7 \times 10^{34}\ cm^{-2}s^{-1}$

7 TeV
Peak luminosity
$2.0 \times 10^{34}\ cm^{-2}s^{-1}$

LHC Injector Upgrade:
- Connection new LINAC4
- Major upgrades many systems: RF, BI, inj./ext. …

High Luminosity Pb
Experimental Upgrade:
- ALICE and LHCb

High Luminosity p:
- Peak luminosity **$5 \times 10^{34}\ cm^{-2}s^{-1}$**
- **$3000\ fb^{-1}$** in 10 years
- Replacement Triplet Quads
- Addition of crab cavities
- Cryogenic upgrade
- Major Experimental Upgrade

2015-16	***2017***	***2018-19***	***2020***	***2021-22***	***2023-24***
p pol., ions	--	Au	--	p pol., Au	--
Coherent e-cooling test Exp. upgrade	Low energy e-cooling upgrade	Exp. upgrade	Exp. upgrade	Exp. upgrade	**Transition to eRHIC**

Based on a slide by B. Mueller presented at the RHIC Science and Technology Review (Sept., 2014).

High Energy Hadron Colliders – Studies

- Parameters under consideration for
  - Future Circulating Collider (FCC)
  - Super Proton Proton Collider (SppC)

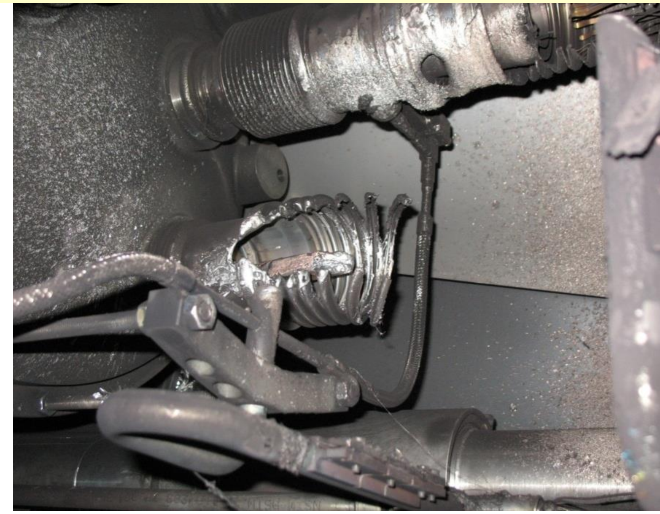
	Circumference [km]	*Physics start date*	*Max. beam energy [TeV/n]*	*av. Beam current*	*Peak Luminosity [$cm^{-2}s^{-1}$]*
FCC-hh pp PbPb pPb *FCC-ee (e+e-)*	100 (80)	2035-2040+	50 19.7	0.5 A 3 mA	5×10^{34} (lev.) 12.7×10^{27} $3\text{-}5 \times 10^{30}$
HE-LHC	26.7		16.5	0.4 A	5×10^{34} (levelled)
SppC (pp) *CEPC (e+e-)*	50-70	2042+	25 – 45	0.4 – 0.5 A	$2\text{-}3 \times 10^{35}$

Challenges related to Beam Diagnostics I

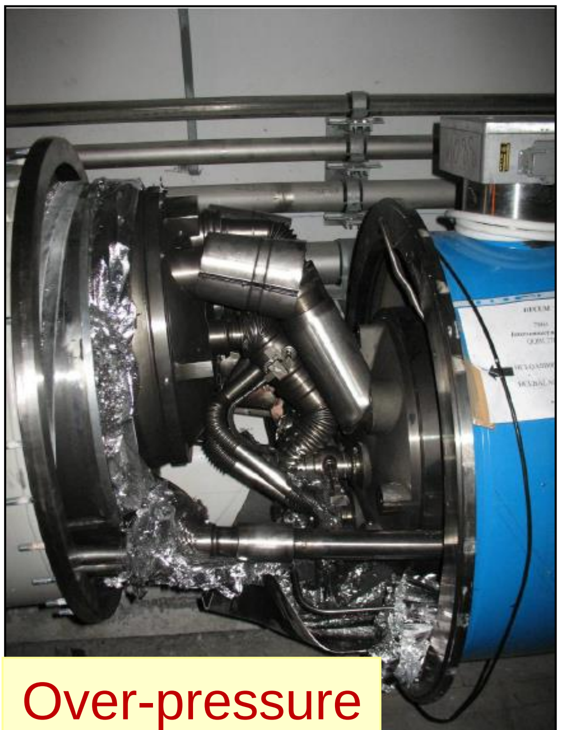
- Stored energy (beam and superconducting magnets), high brightness beams
  - Avoid uncontrolled losses
    - Machine protection
      - BI systems part of machine protection require high dependability
        - Loss monitoring, certain BPMs, fast current change monitors
    - Collimation and related monitoring
    - Halo Monitoring
  - Avoid intercepting measurement devices
    - Quench magnets
    - Get destroyed by the beam
    - → Non-invasive monitoring of all relevant machine parameters!
  - Small beam sizes
    - Systematic effects dominate the measurement

Energy stored in the Magnets – release of 600 MJ

- LHC 2008 incident **without beam**
  - Electrical arc provoked a He pressure wave damaging ≈600 m of LHC
- LHC magnets at 7 TeV: 10 GJ



Arcing in the interconnection



Over-pressure

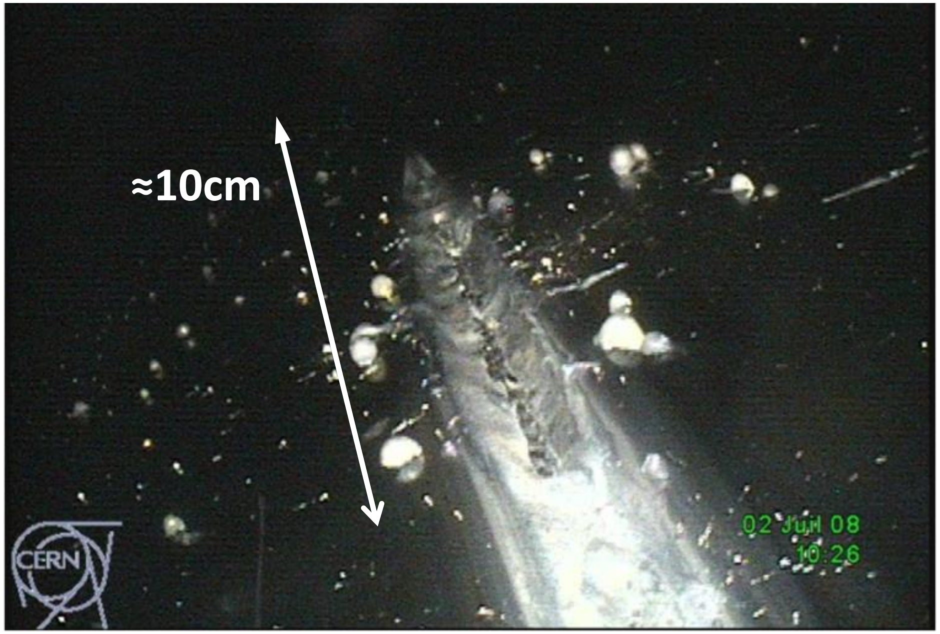
Magnet displacement

Energy stored in the Beams – uncontrolled Losses

- LHC at 7 TeV 360 MJ:
  - Pilot bunch of 5×10^{9} close to damage level
  - Loss of 3×10^{-7} of nominal beam over 10ms can create a quench

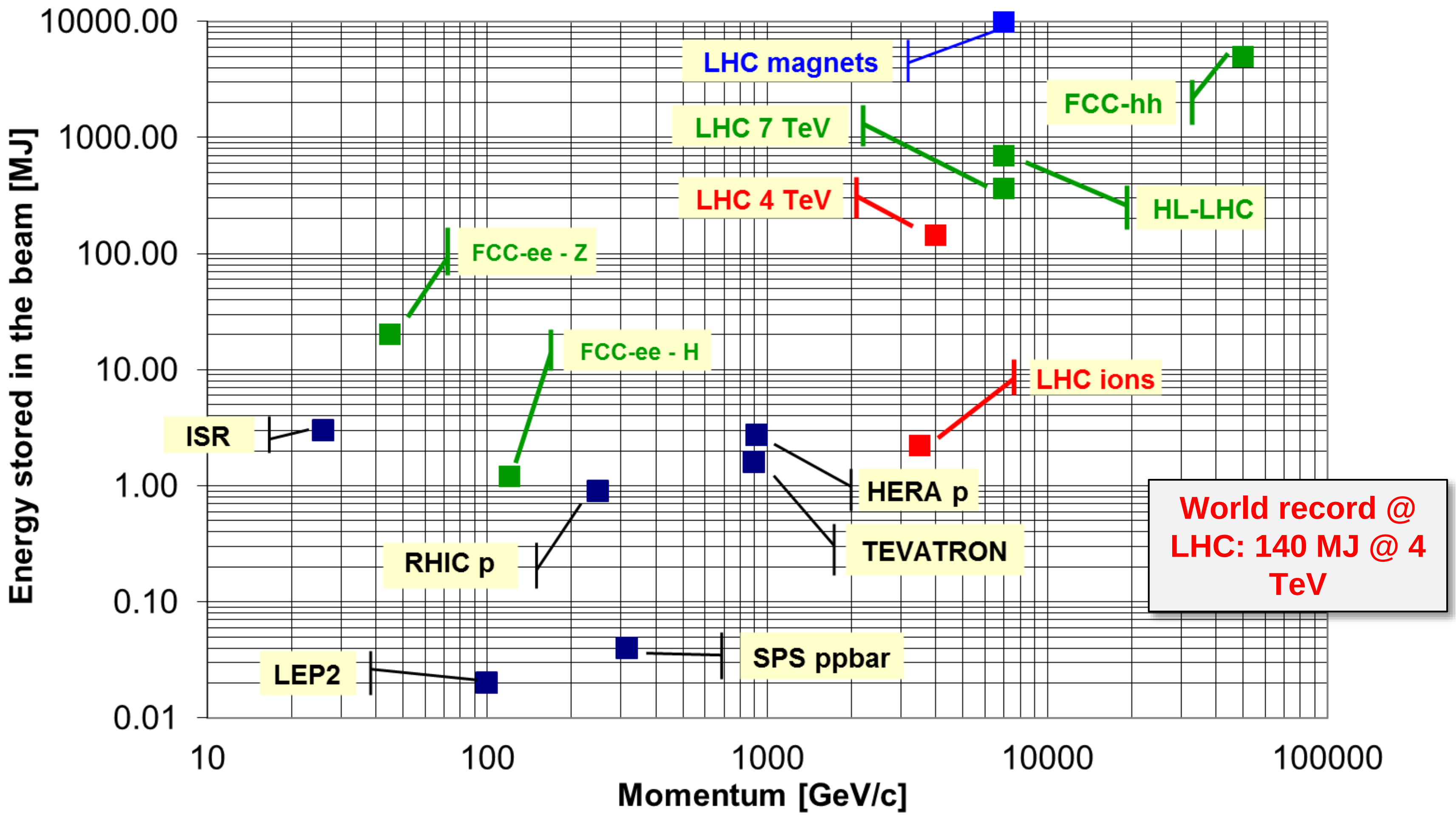
1MJ can heat and melt 1.5 kg of Copper

- SPS incident in June 2008 400 GeV beam with **2 MJ** (J. Wenninger, CERN-BE-2009-003-OP)



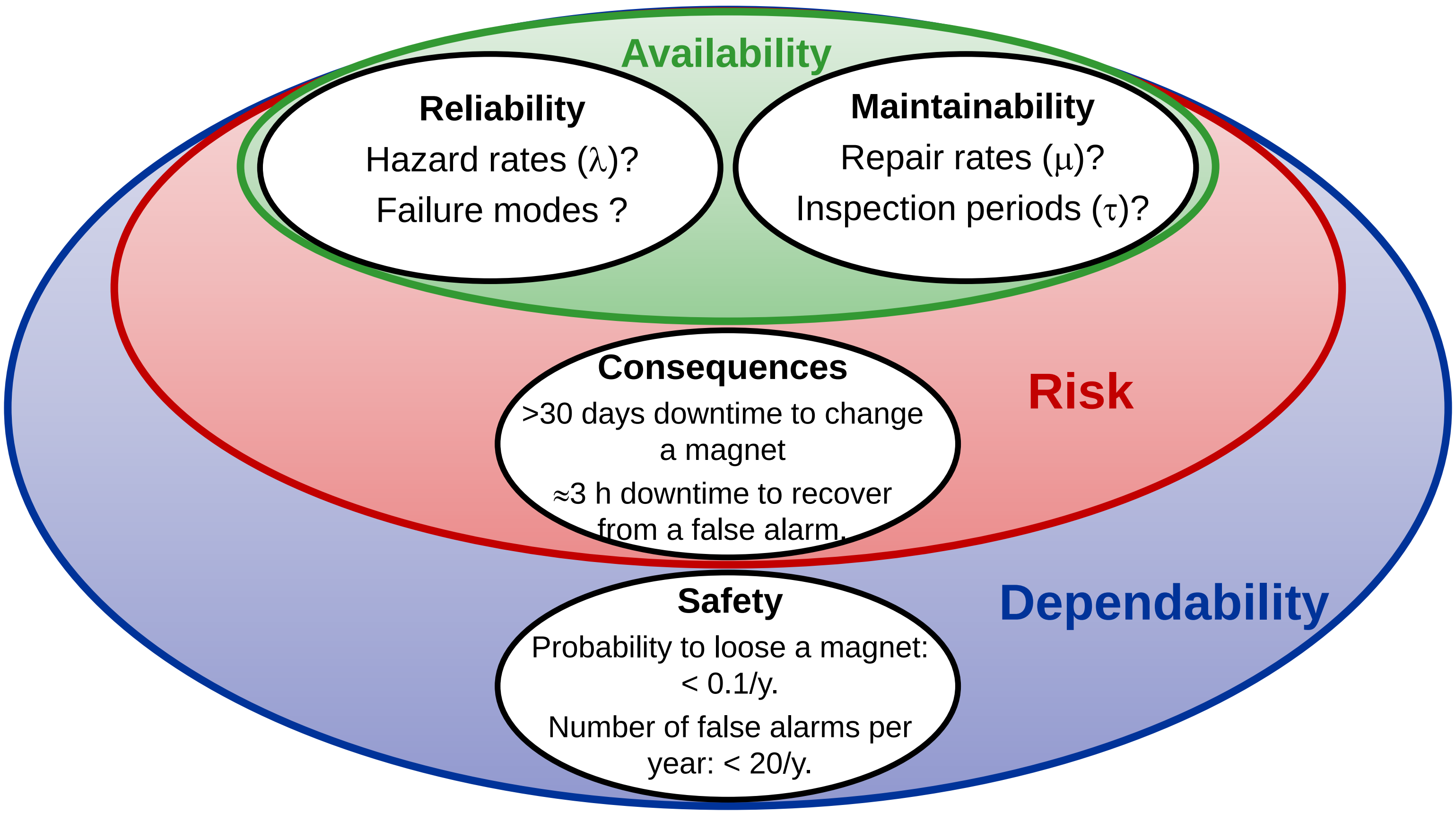
Stored Beam Energy

- **LHC 7 TeV:** 360 MJ
- **HL-LHC: 694 MJ**
- **FCC-hh: 8 GJ**
- HE-LHC: 0.7 GJ



Dependability (colloquially: reliability) analysis

- Machine protection system must be integrated in the machine design
- Dependability (reliability, availability, maintainability and safety) analysis → Budgets for
  - Probability of component damage due to malfunctioning
  - Downtime due to false alarms
  - Downtime due to maintenance



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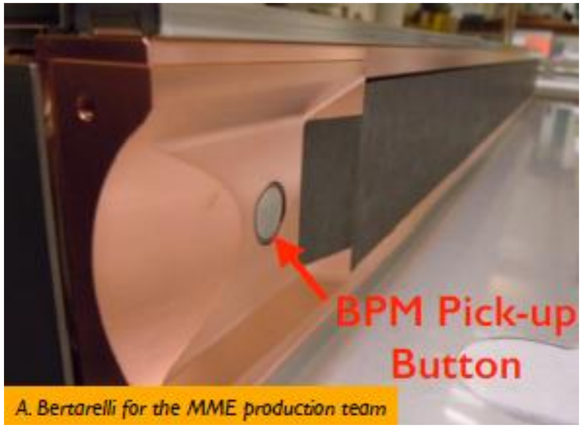
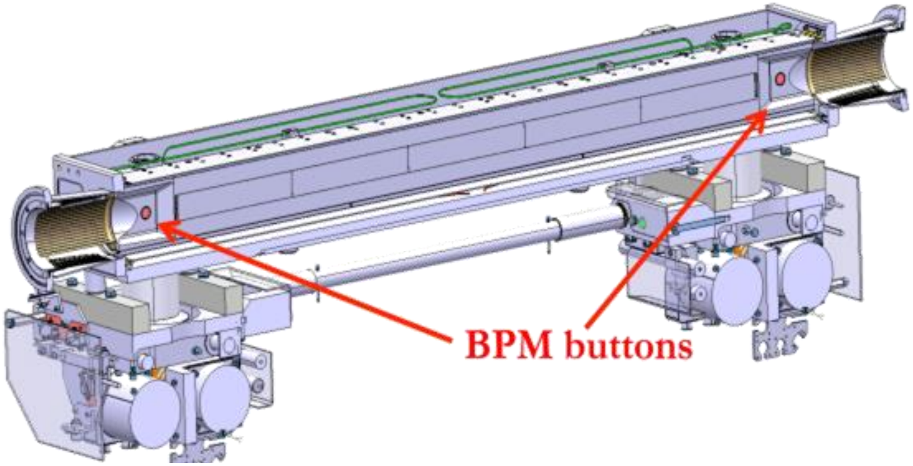
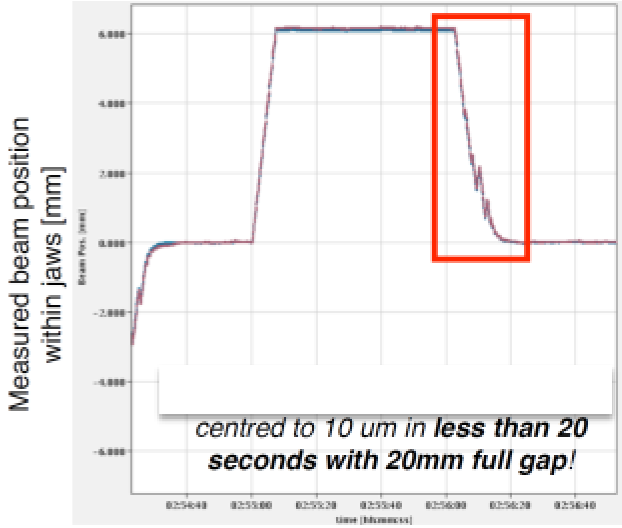
New LHC Collimators with Embedded BPMs

- 18 collimators now equipped with BPM buttons
- Readout via compensated diode peak detectors (Diode Orbit electronics)
  - Resolution <100nm for centered beams
- Fast, parallel alignment:
  - <20 s for all BPM collimators without touching the beam
  - 2 orders of magnitude faster than BLM method
- Constant monitoring of beam position → tighter collimator settings →smaller β*

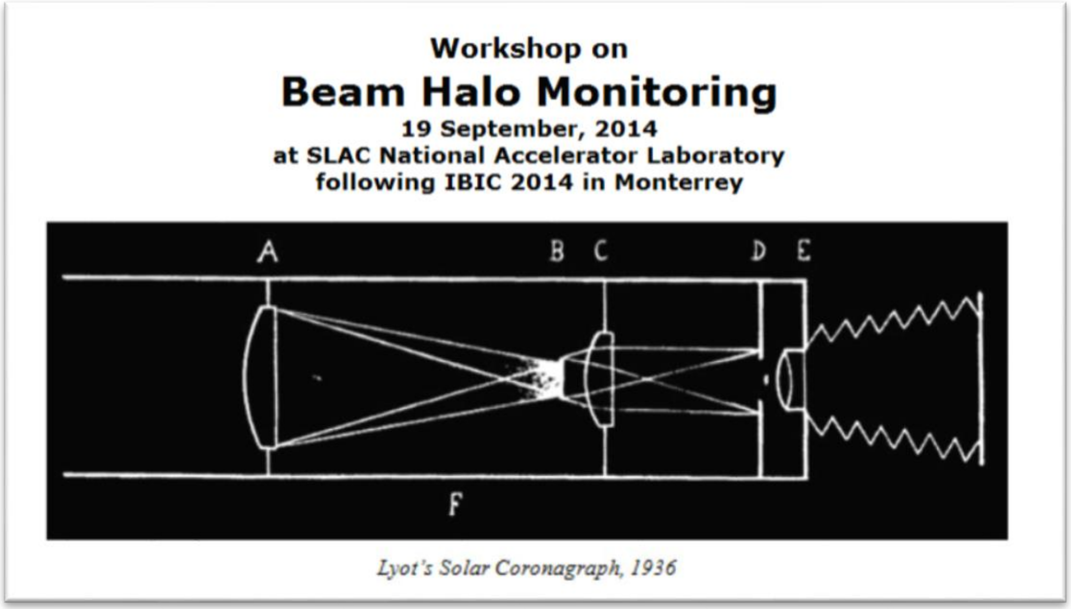






Halo Monitoring

- See overview presentation of K. Wittenburg on Tuesday and other contributions in this workshop



- Kay Wittenburg, *Beam Halo and Bunch Purity Monitoring,* CAS on beam Diagnostics, Dourdan, CERN-2009-005 (2009).
- 29th ICFA Advanced Beam Dynamics Workshop on Beam Halo Dynamics, Diagnostics, and Collimation, HALO'03, Montauk, Long Island, New York.
- Proceedings of HB workshops

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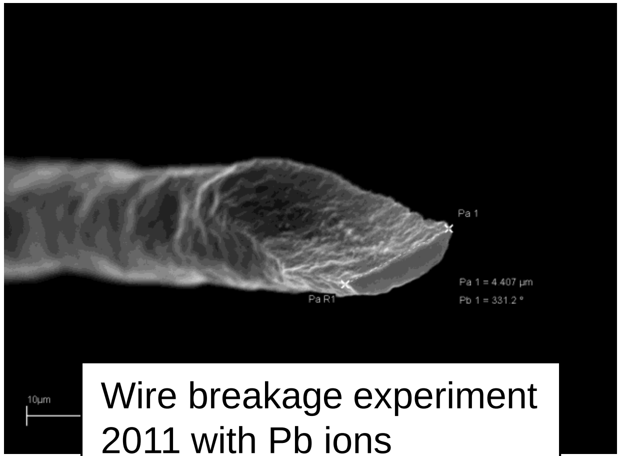
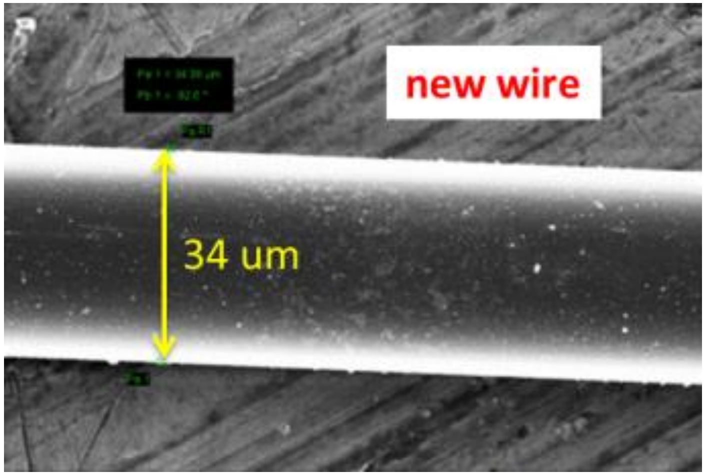
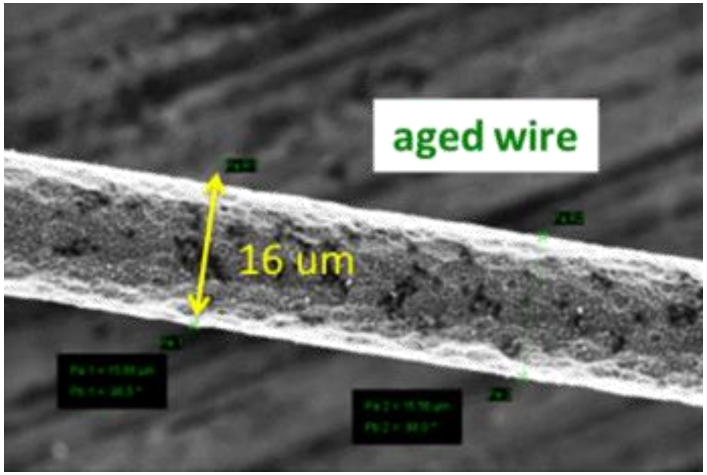
LHC Wire Scanner

- Needed to calibrate all other LHC beam size measurements
- At 450 GeV limit at 2.7×10^{13} protons by wire breakage
  - One injected batch of 144 bunches @ 50ns OK
  - One injected batch of 288 bunches @ 25ns NOT OK
- At 6.5 TeV limit at 2.7×10^{12} protons by the quench limit of cold magnet
  - ≈20 bunches
- Aging due to wire sublimation


Wire breakage experiment 2011 with Pb ions



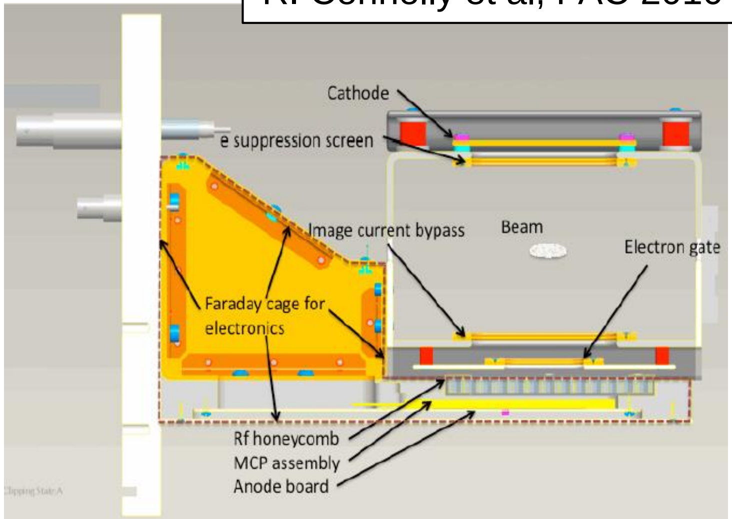


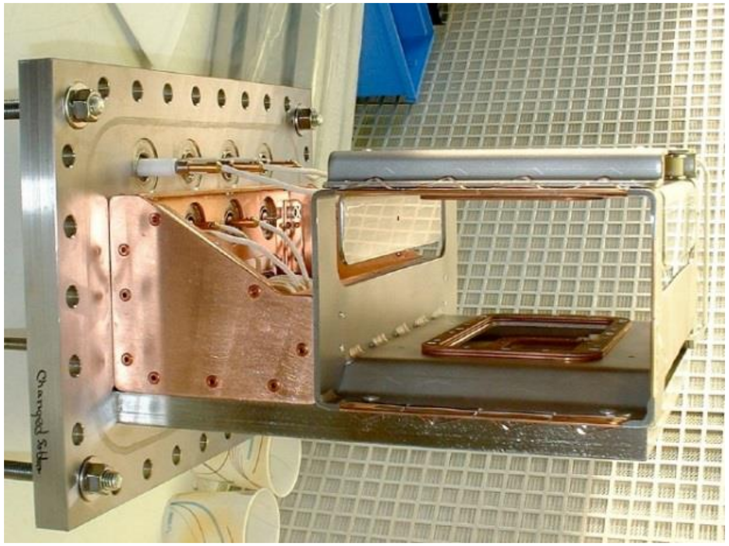
Courtesy M. Sapinski

RHIC Ionization Profile Monitors (IPM)

R. Connolly et al, PAC 2010

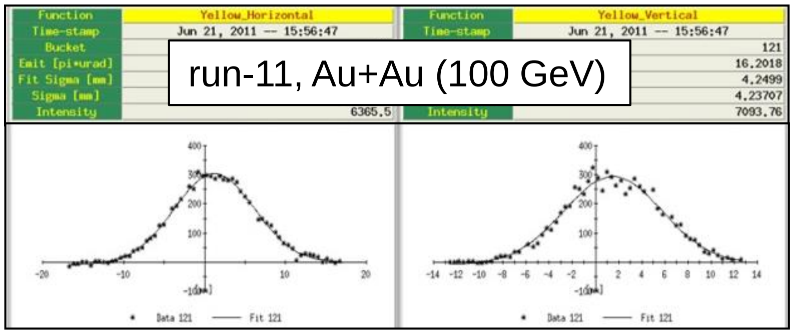
- e⁻ from beam-rest gas interaction accelerated towards readout by E-field
- Guiding B-field
- Amplification by Multichannel plate (MCP)
- 64 strip anode readout
- Fast signal gating to reduce aging of the MCP
- Readout inside a Faraday cage to shield it from the beam's image current
- single bunch and single turn

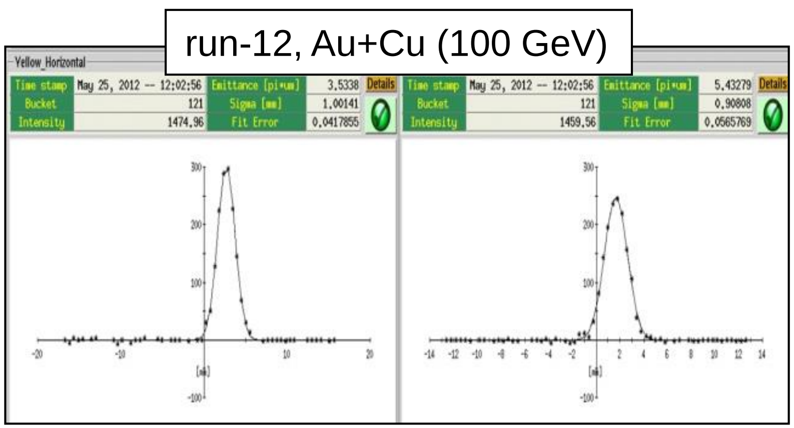




RHIC IPM – recent Improvements

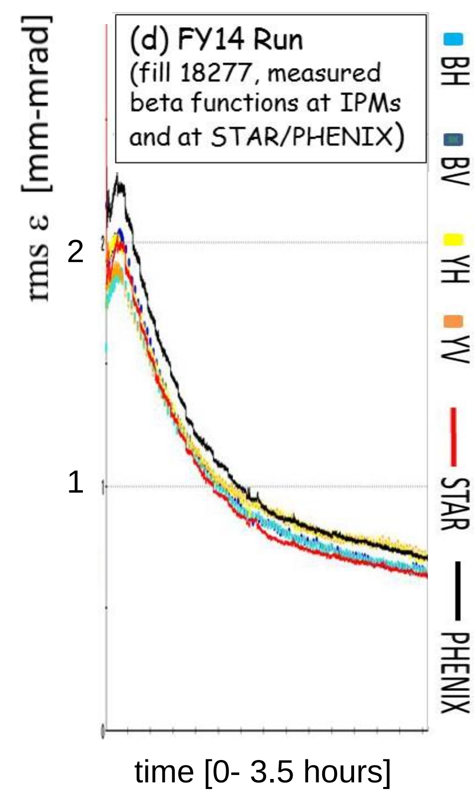
Beam based offset and gain calibration





Absolute emittance measurement by using measured beta function:

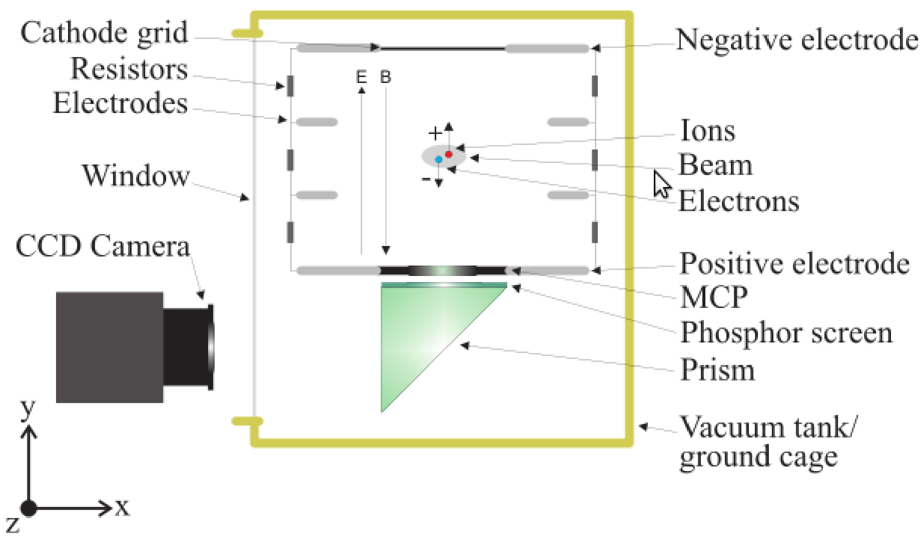
- Convergence of horizontal and vertical emittances of both beams under optimized 3D stochastic cooling
- Agreement within 15% with the emittances measured by the experiments STAR and PHENIX

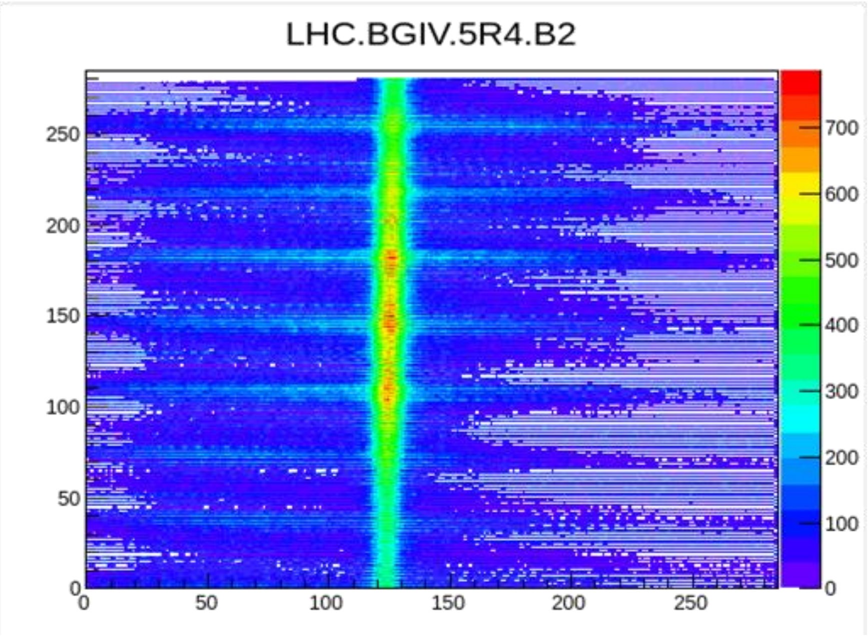


M. Minty et al. IBIC 2014

LHC Ionization Profile Monitor

- Gas injection (Ne)
- Electron collection with 0.2 T guide magnets and MCP signal amplification
- Optical readout from phosphor screen with Radiation-hard camera
- Worked well for Pb ions (what it was designed for)

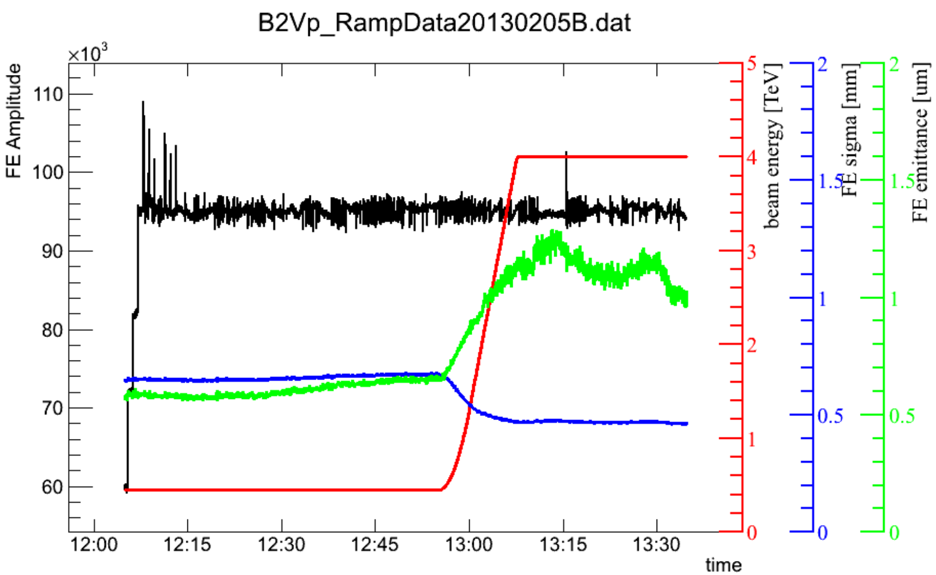


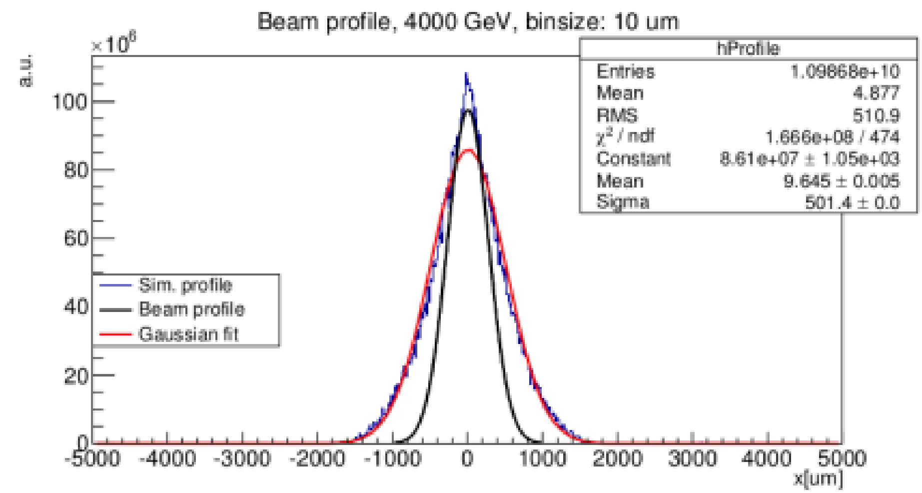


LHC Ionization Profile Monitor for Protons

- Measured emittance at injection agrees with wire scanner
- When charge density increases → space-charge leads to profile distortion → signal non-gaussian and dominated by systematic effect at 7 TeV
- Increase of magnetic field to 1 T would allow direct measurement
- Try to find and algorithm to disentangle the beam size

poster by M. Sapinski

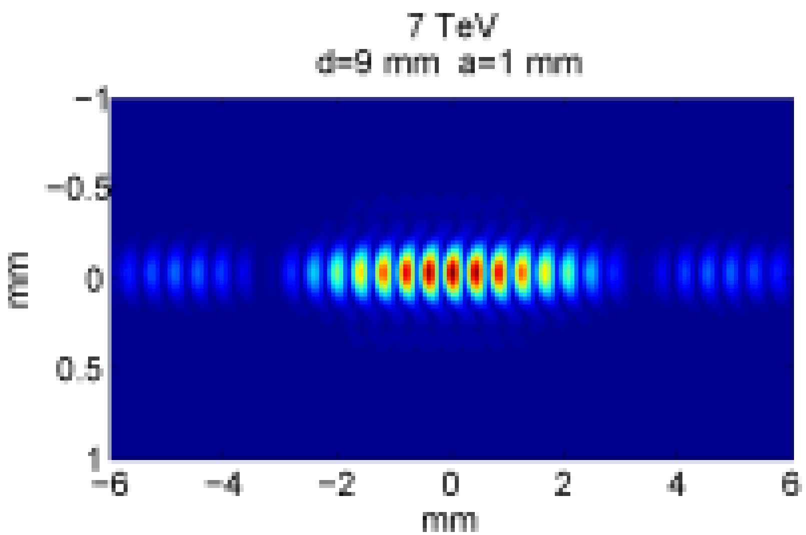




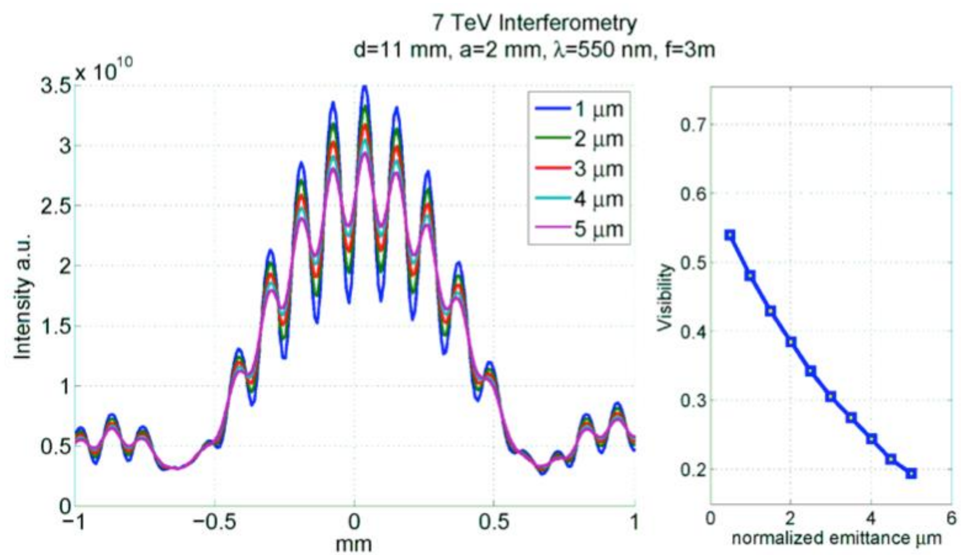
Measurement of small beam sizes using the synchrotron light monitor at the LHC

- At 7 TeV even using UV (250nm) the imaging will be diffraction dominated (≈250mm > beam size of 180mm)
  → adding an optical line for interferometry (collaboration with KEK, SLAC and CELLS-ALBA)
  - Non-diffraction limited and widely used in e⁻ machines for very small beam sizes

Visibility = $(I_{max} - I_{min}) / (I_{max} + I_{min})$



Simulated interference fringes at 7 TeV

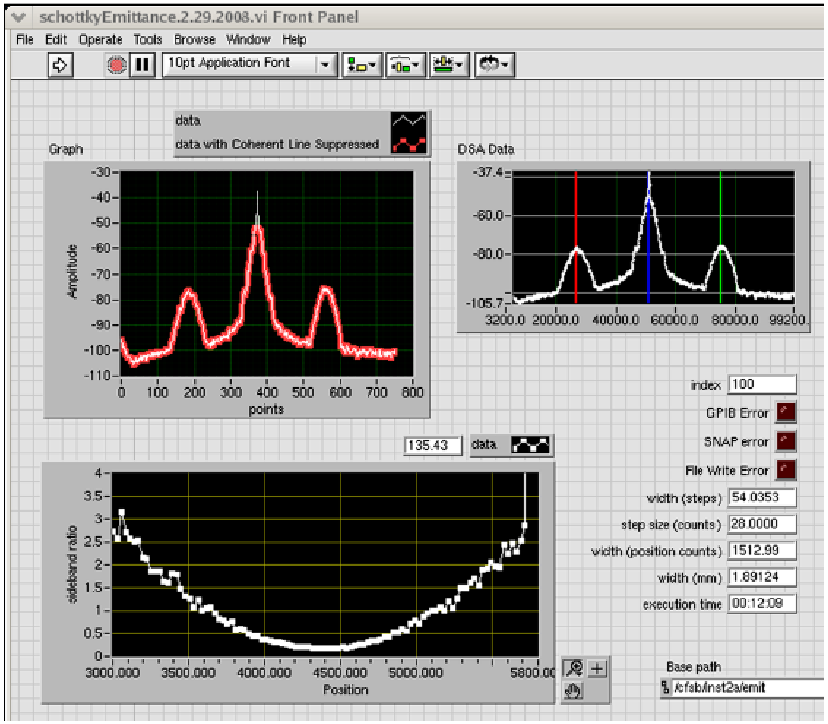


Interference fringes for different emittances and predicted visibility as function of emittance

RHIC Schottky transvers Emittance Measurement

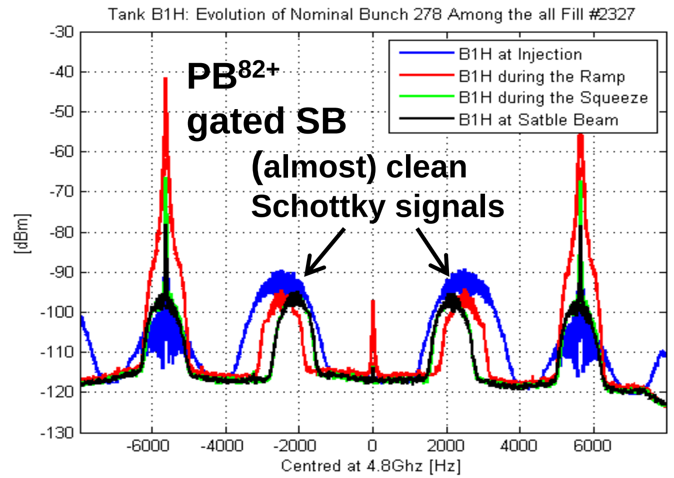
- High frequency cavity operated at 2.07 GHz
- **Absolute transvers emittance** measurement demonstrated
  K.A. Brown et a., Phys. Rev. ST Accel. Beams 12, 012801 (2009)
  - Moving the cavity transversally to the beam and recording the spectrum at each position
  - Power in the band of the revolution harmonics is proportional to the square of the distance of the orbit from the center of the cavity
  - Sum of the power in the two betatron side-bands is proportional to the square of the rms beam size

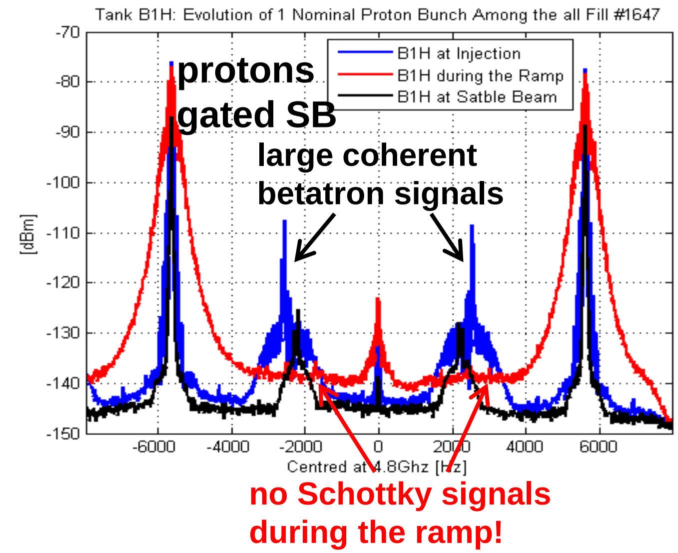
→ 20% uncertainty in transverse emittance in 2008 measurement



LHC transvers Schottky Measurements

- Slotted waveguide pick-up operated at 4.8GHz
  - High enough to have small coherent signals
  - Low enough not to have band overlap
- Triple down-mixing
- 25ns gating for individual bunch measurement
- Aim: on-line chromaticity and bunch by bunch tune
- Run1: successful for ion beams
- Currently: Design changes to improve performance for protons

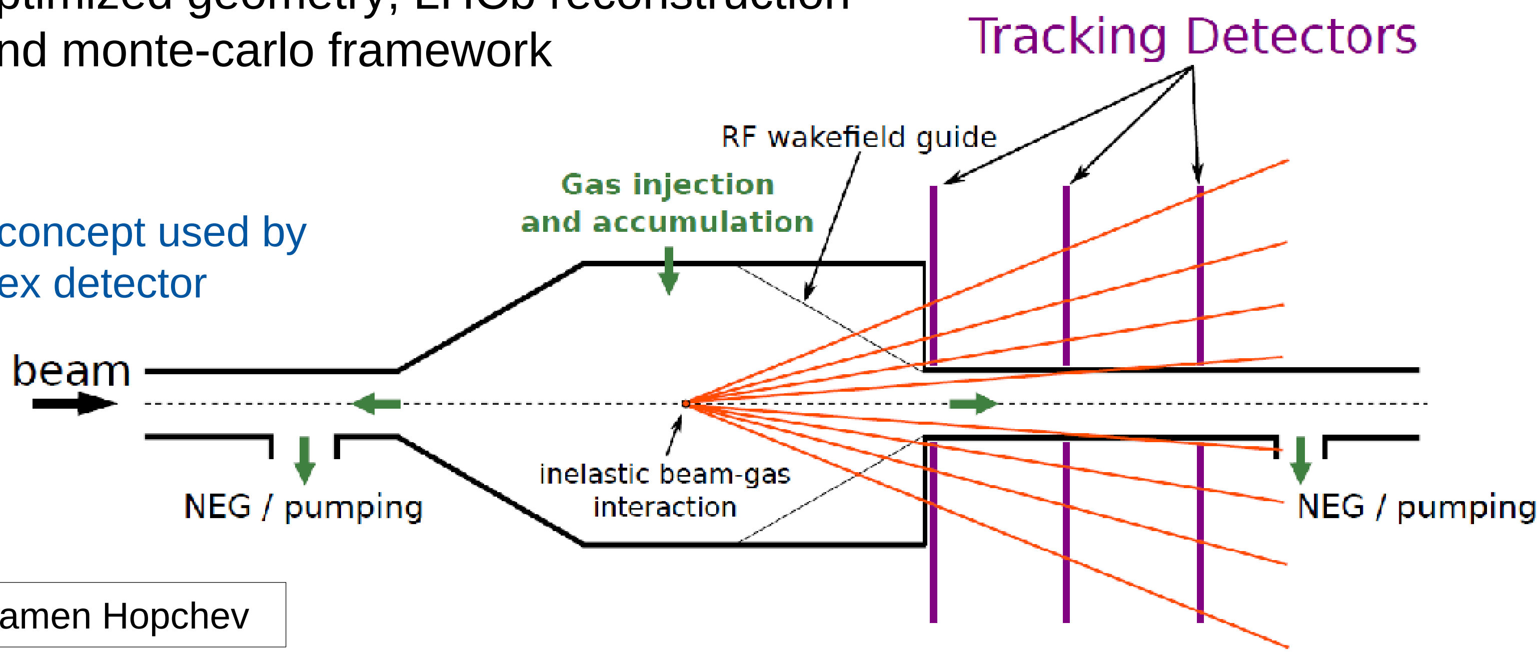




Beam Gas Vertex Monitor (BGV) – Novel Design

- Non-invasive *and* absolute transvers profile measurement
- Reconstruct the location of inelastic beam-gas interactions (vertex) with particle tracks
- Accumulate vertices to measure beam position, angle, width and relative bunch populations. Require:
  - Sufficient beam-gas rate → controlled pressure bump
  - Good vertex resolution → precise detectors; optimized geometry; LHCb reconstruction and monte-carlo framework

Based on concept used by LHCb vertex detector



Courtesy Plamen Hopchev

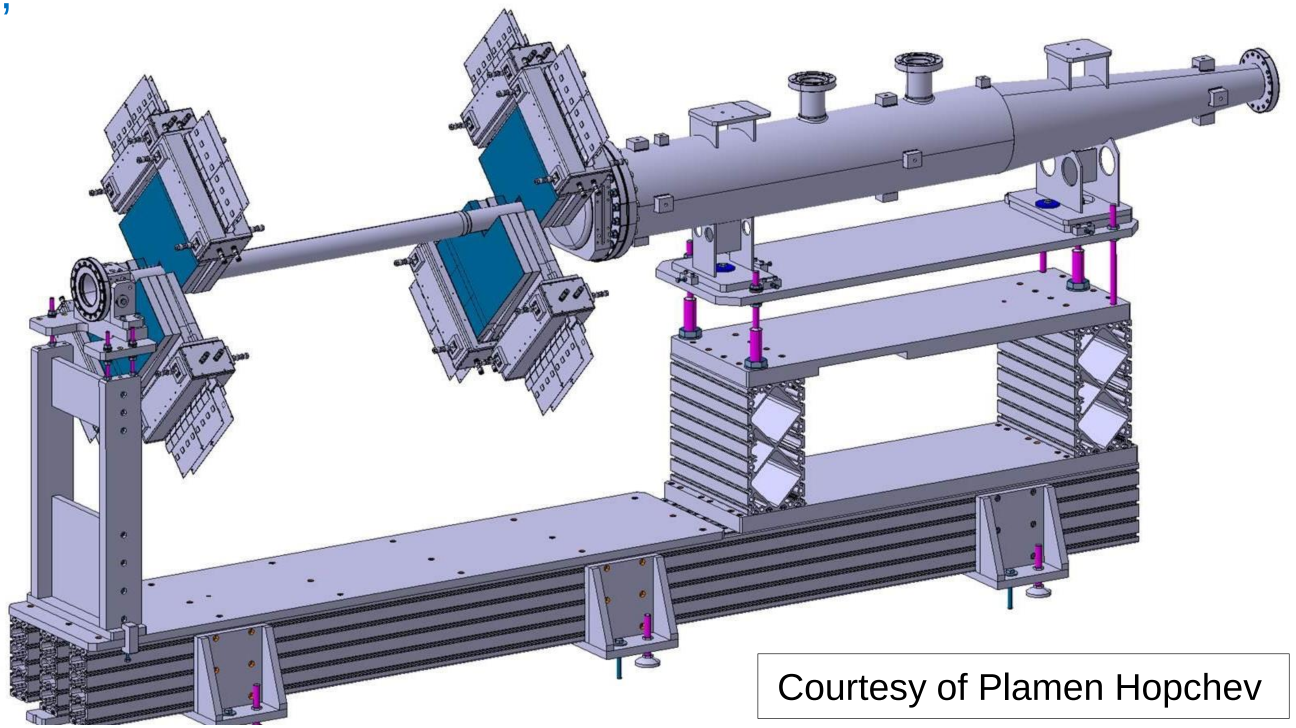
BGV Demonstrator

- **Prototype** BGV system on one beam at the LHC
- Commissioning planned for 2015
- Collaboration with: LHCb (CERN), EPFL (CH), Aachen (DE)

Aim for the **final instrument** (HL-LHC) / **prototype**

Quantity	Accuracy	Time interval	Key factors
Relative bunch width	**5% / 5%**	**<1 min / 5 min**	vertex resolution stability
Absolute average beam width	**2% / 10%**	**<1 min / 1 min**	σ_{beam}, σ_{MS}, σ_{extrap} (σ_{hit})

Detector
- Scintillating fibres read out with SiPMs
- Same technology as for the LHCb upgrade



Courtesy of Plamen Hopchev

Challenges related to Beam Diagnostics II

- Large size of the colliders
  - Number of components
    - Cost
    - Maintainability
    - Data handling, monitoring, logging, analysis
  - Readout electronics
    - either close to instrument → radiation hard
    - Or long cables → noise, losses

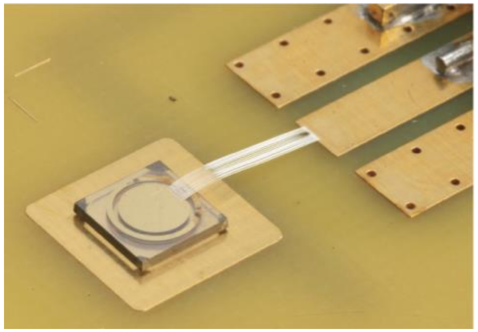
    → prefer optical diagnostics and optical signal transmission
- High radiation levels (IPs, collimation, …)
  - Radiation hard equipment
  - Interfere with los measurements

Challenges related to Beam Diagnostics III

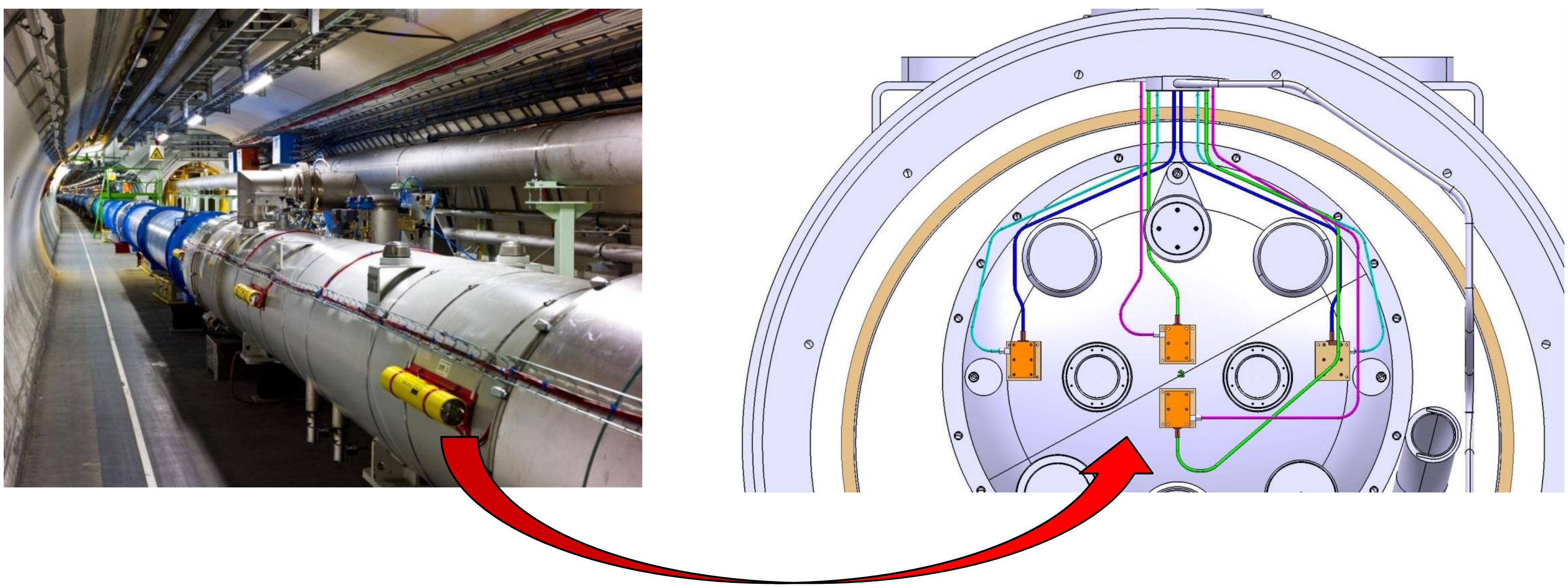
- Instruments in cryogenic temperatures (BPMs, BLMs)
  - New regime (BLMs)
  - High dependability (feedthroughs etc.)
- Monitoring of beam instabilities
  - Bunch-by-bunch and intra-bunch measurements
  - Improved performance required e.g. for reliable feed-back systems
    - RHIC: orbit, tune and coupling feedback was a key to higher luminosities, polarization and integrated luminosity/uptime
    - LHC: orbit feed-back, tune feed-back only at selected periods during the cycle
- Wakefields and RF heating
  - Very strict impedance budget
    - Particularly for devices which are numerous (BPMs)
  - Damage due to RF heating

Beam Loss Monitoring at Cryogenic Temperatures

- Loss monitor closer to loss location → avoid that the signal is dominated by other radiation sources (e.g. physics debris)
  - Investigated: LHe, silicon, diamonds
  - First tests in the LHC in 2015

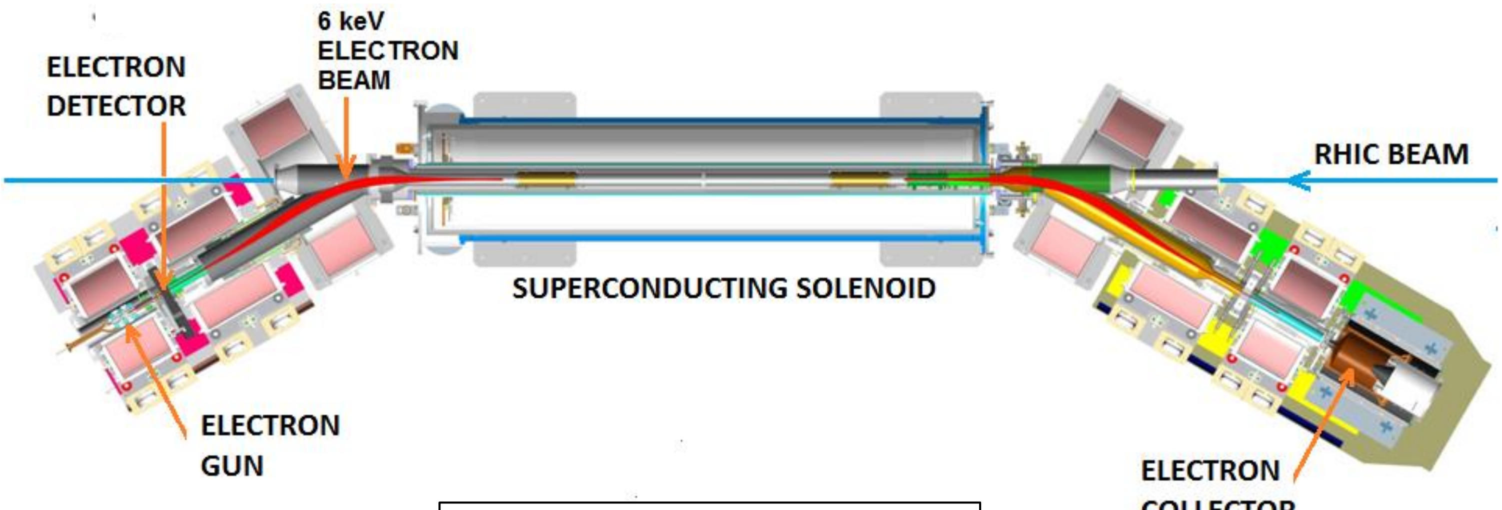


Diamond BLM detector, courtesy of E. Griesmayer



ELECTRON BACKSCATTERING DETECTOR (eBSD)

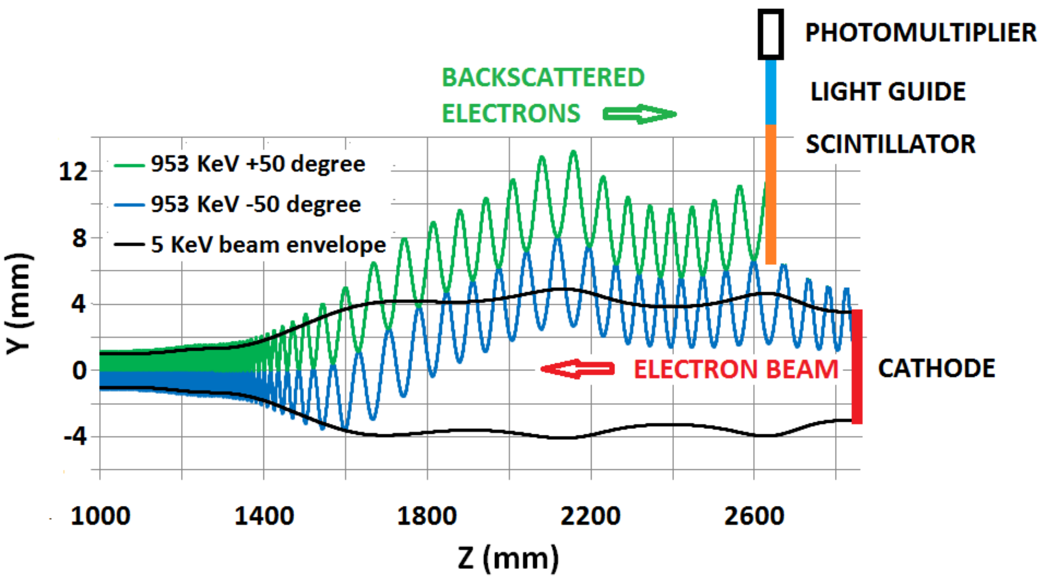
- Aim of the RHIC electron lens
  - Partially compensate the beam-beam effect → higher polarized proton luminosities
  - non-linear focusing by low energy (≈6 keV), high intensity (≈1 A) electron beam
  - 2 m interaction region in the ≈6 T solenoid, the centers of these ≈300 μm rms wide beams need to be aligned to less than 50 μm



P. Thieberger et al., IBIC 2014

ELECTRON BACKSCATTERING DETECTOR (eBSD)

- New tool for the precise alignment of electron with ion beam
- Small plastic scintillator installed close to the e-gun
  - Measures back-scattered electrons
- Automatic procedure for beam alignment by maximizing eBSD counting rates



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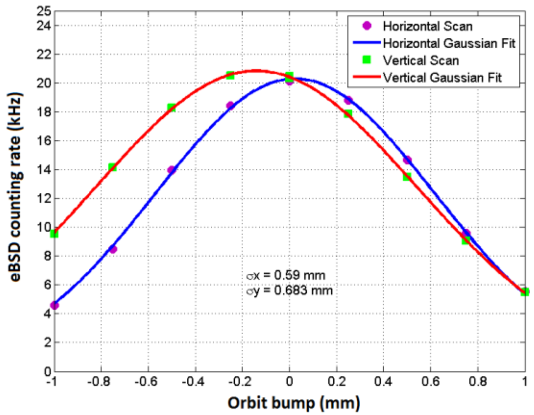
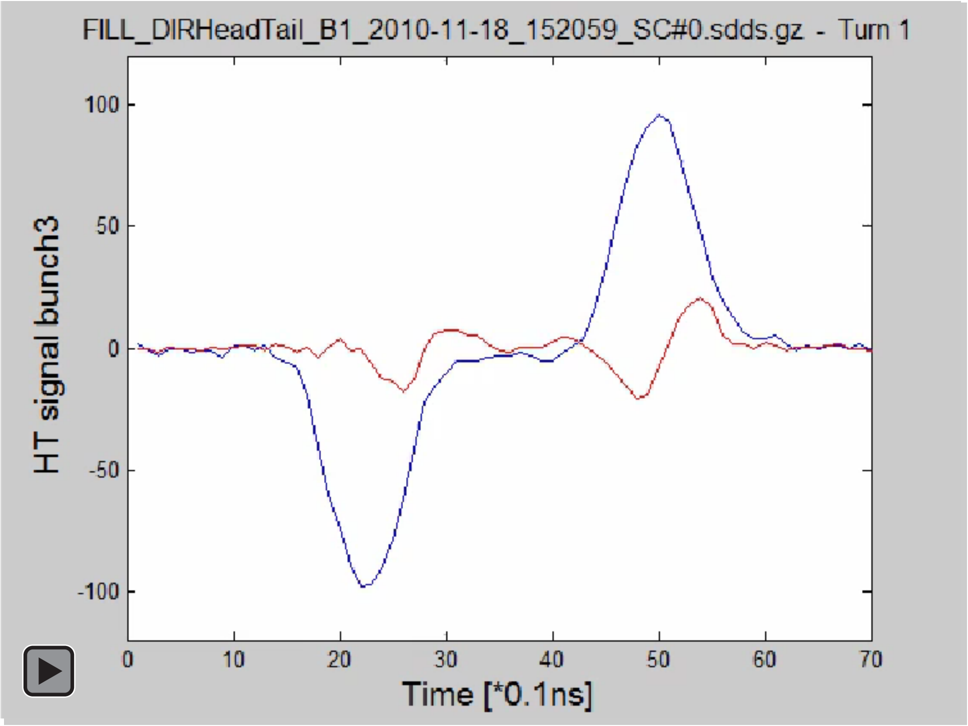
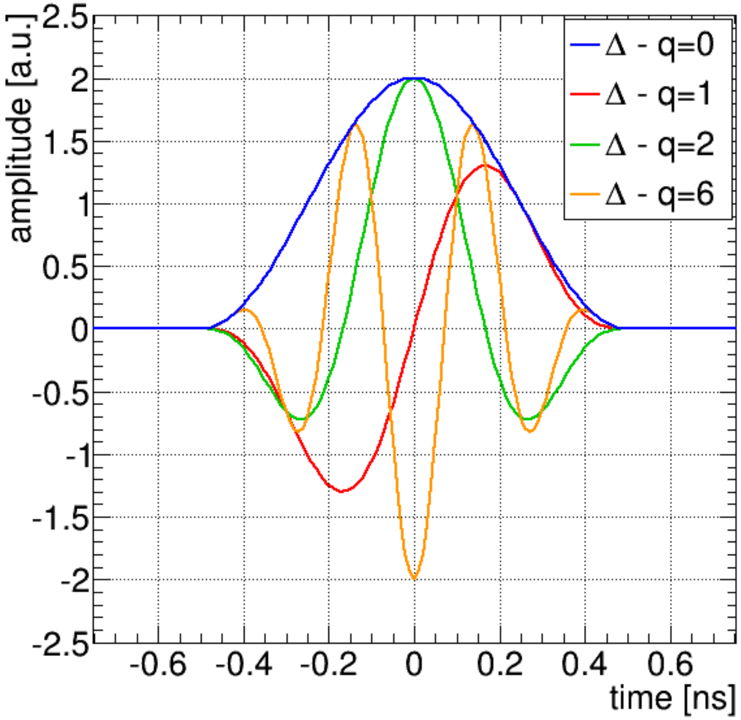


- Might also be used for hollow electron lens considered as option for HL-LHC (CERN_LARP collaboration), based on Tevatron lens design

Intra-bunch Measurements LHC

- Head-Tail monitor
  - Resolution limited to ≈100 μm
- Multiband Instability Monitor – currently being developed
  - Monitors 16 frequency bands individually (Δf_b = 400 MHz)
  - Trigger high rate acquisition of other systems; potential to reconstruct mode of oscillation





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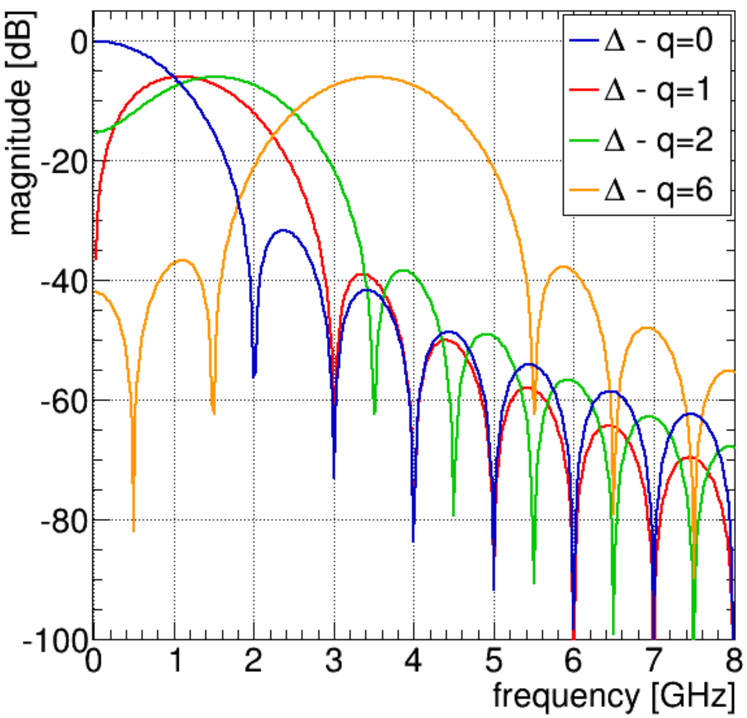

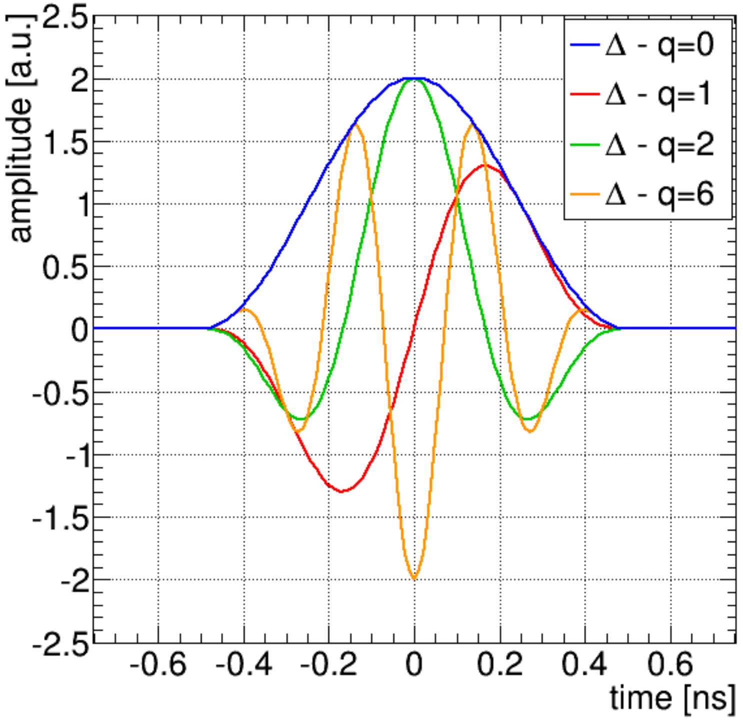

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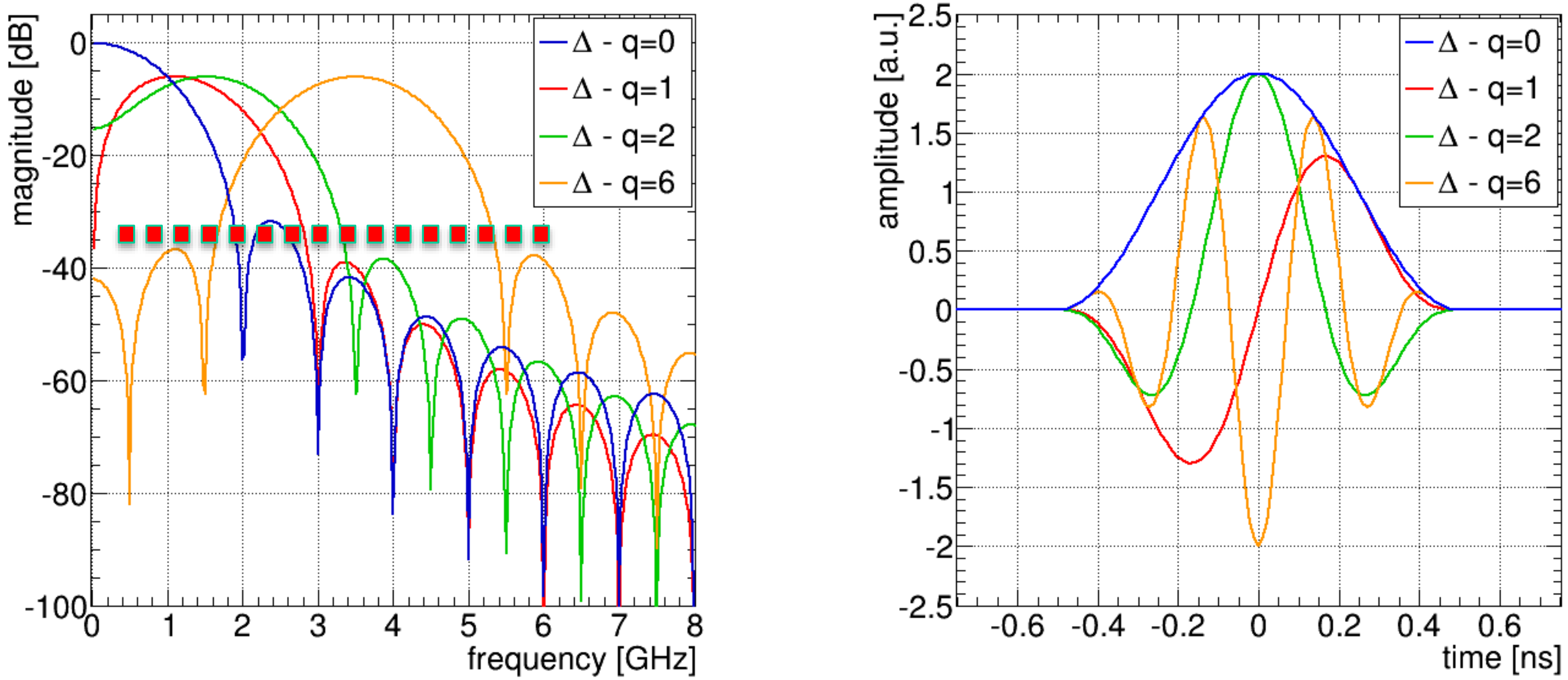

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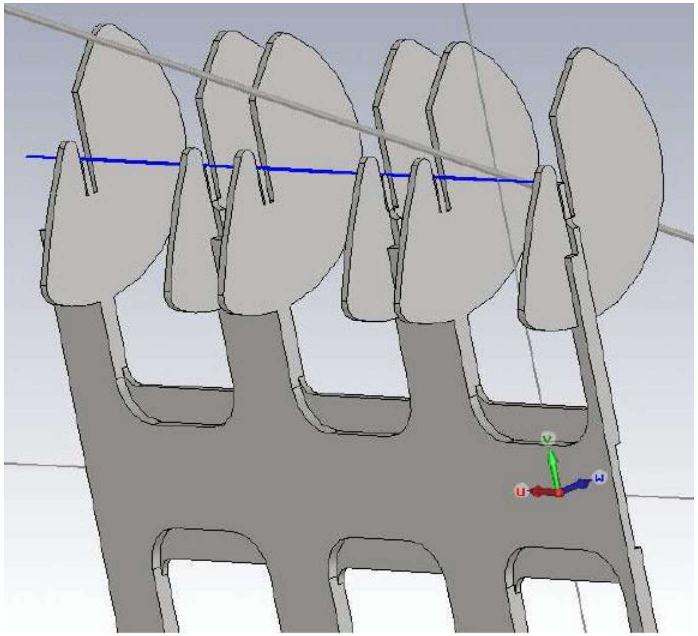
- Monitoring of beam instabilities
  - Bunch-by-bunch and intra-bunch measurements
  - Improved performance required e.g. for reliable feed-back systems
    - RHIC: orbit, tune and coupling feedback was a key to higher luminosities, polarization and integrated luminosity/uptime
    - LHC: orbit feed-back, tune-feed-back only at selected periods during the cycle
- Wakefields and RF heating
  - Very strict impedance budget
    - Particularly for devices which are numerous (BPMs)
  - Damage due to RF heating

RHIC p-Carbon Polarimeter Target

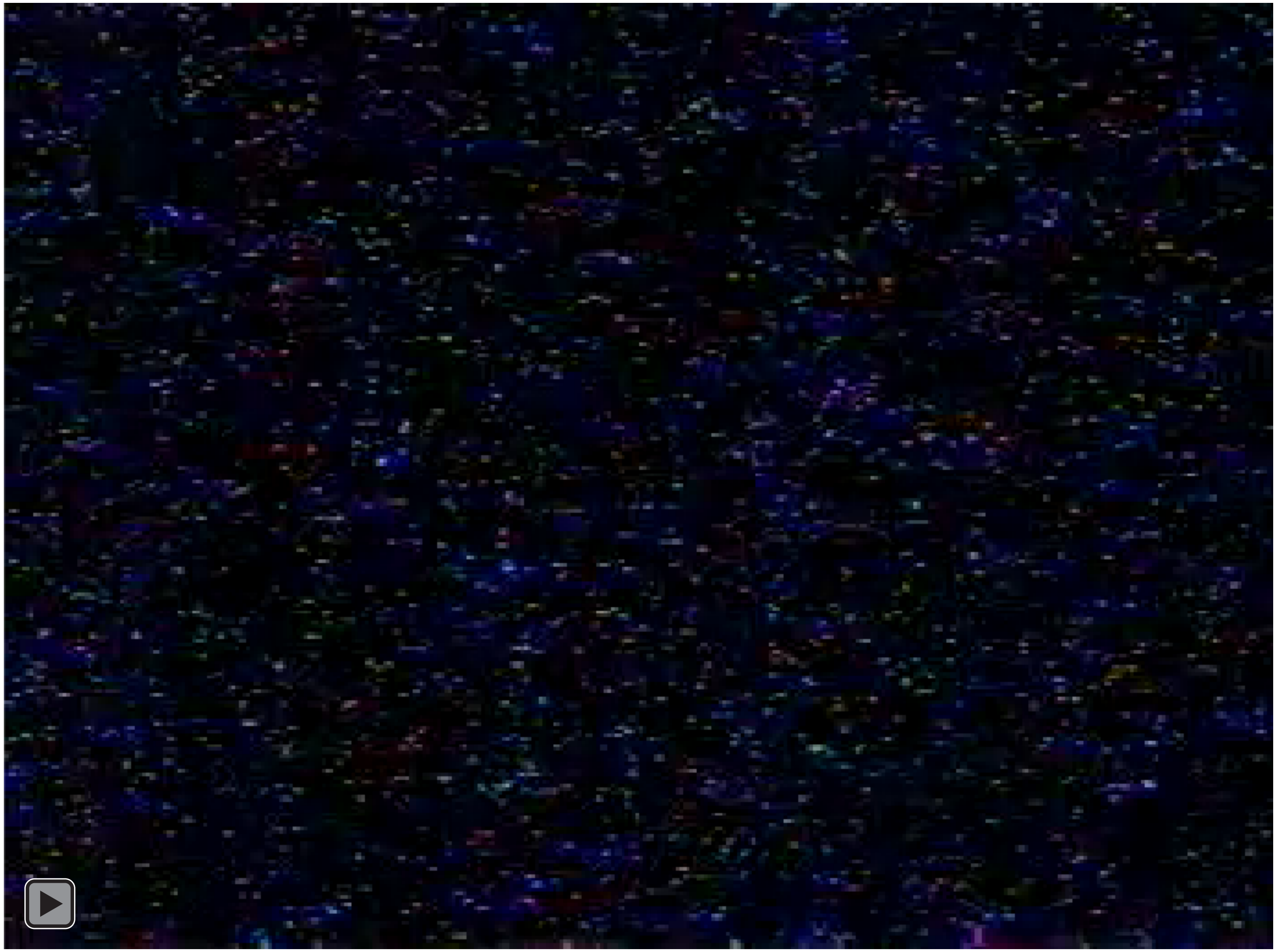
- Thin carbon ribbons (25-100 nm thick, 1-10 μm wide, 2.5 cm long)
- Scanned through the p beam to measure beam polarization profiles
- Frequent target breakage (also without beam contact, even in park position)
  → installation of cameras
  → RF heating at the wire ends without touching the beam



→ Add "fins" to deviate the EM field from the wire ends reduces significantly the heating

H. Huang et al., IBIC 2014

Video 2



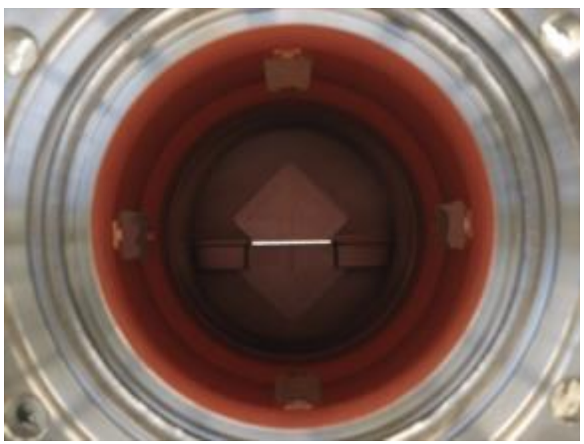
Courtesy M. Minty

- http://www.youtube.com/watch?v=hQsOAyQ7Kck

Beams induced RF heating – LHC run1

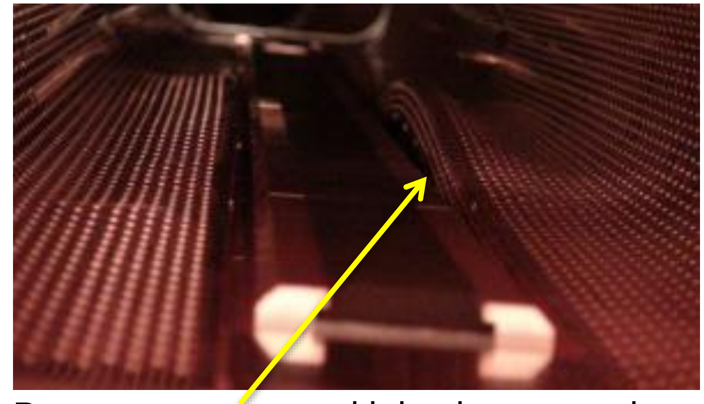
Overheating → pressure rise

Injection Kicker

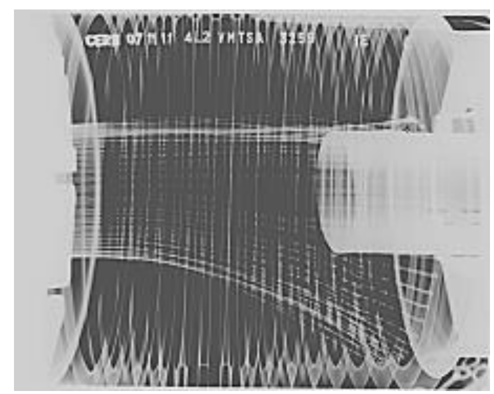


ATLAS ALFA Detector

Material deformation



Beam screen around injection protection jaw

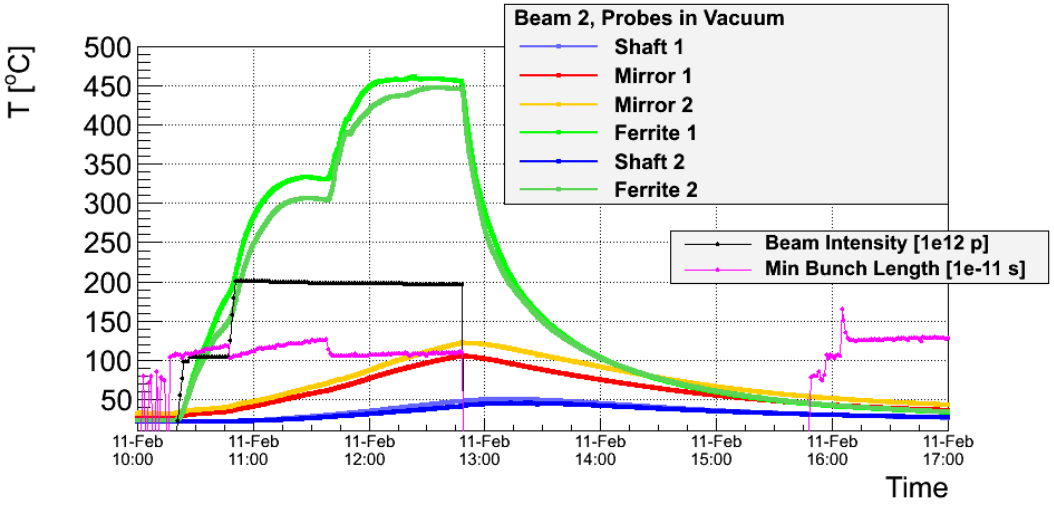


RF contact fingers at magnet interconnects

Synchrotron Light Extraction Mirror

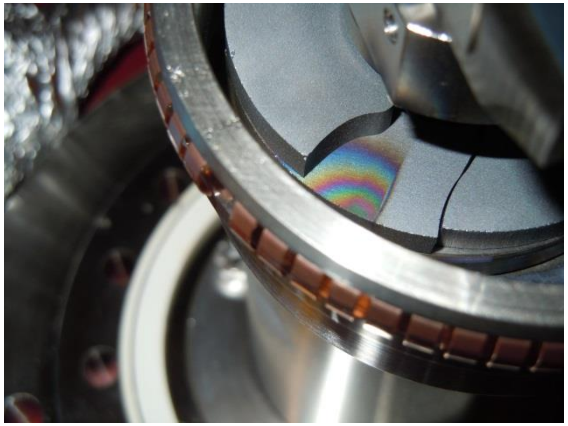
Mirror heating correlated to:

- Beam intensity
- Bunch length
- Beam spectrum



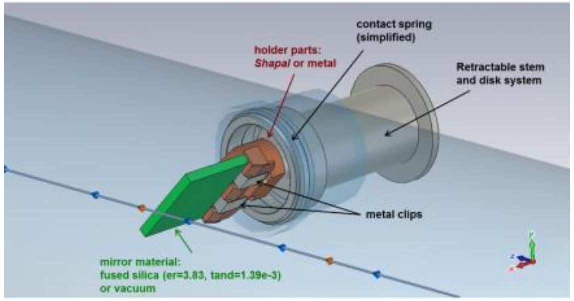
Failure of mirror holder + blistering of mirror coating

Overheated and broken ferrite absorbers (BSRT)

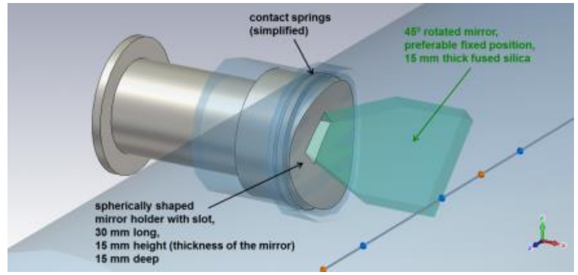


RF Heating cont.

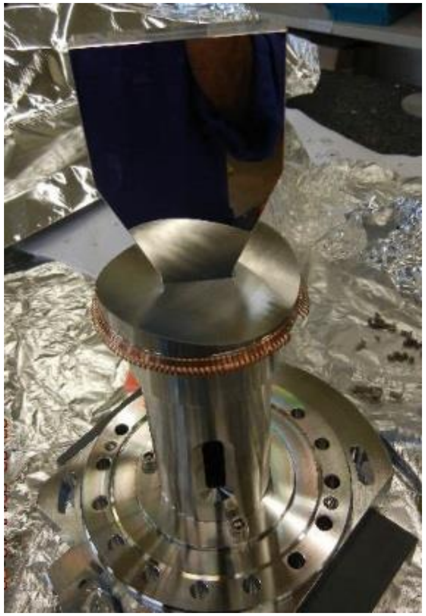
OLD Extraction Mirror



NEW Extraction Mirror



Solution for Run II with low RF 'footprint' and shielded cavities



- EM simulations and lab tests are essential for all equipment which is installed on the beam
- Mitigation by e.g.:
  - Design changes to reduce the build-up of wake fields – or deviate from the sensitive location
  - Adding ferrites to absorb the RF power given there is sufficient cooling for the ferrites
  - Multi-mode couplers to extract the power and dissipate it outside of the vacuum

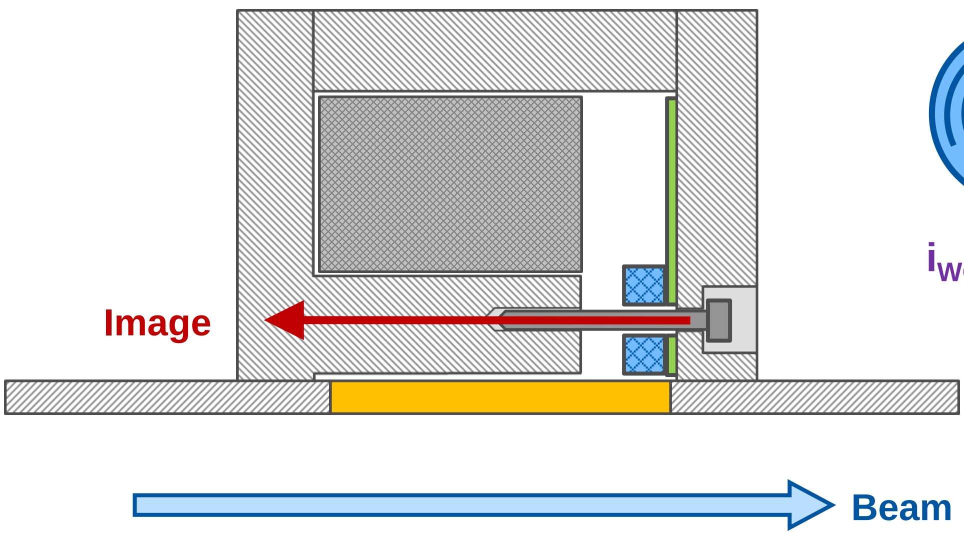
Summary

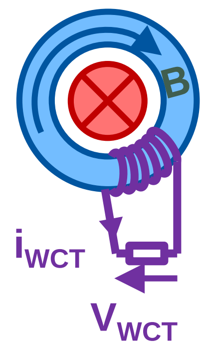
- Challenges:
  - Dependability (availability, reliability, maintainability, safety)
  - Instabilities
    - Bunch / intra-bunch measurements
    - Measurement stability, precision, resolution → feedback
  - Non-invasive measurements
  - Wakefields / RF heating

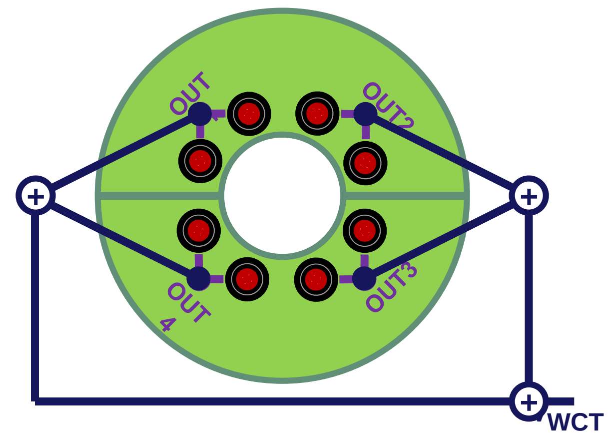
Thank you for your Attention

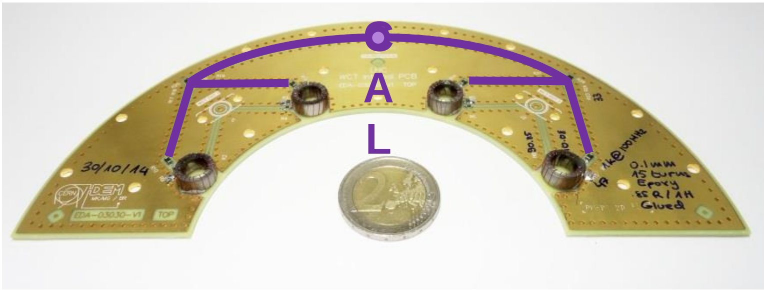
Wall Current Transformer for Intensity Measurement

- New device developed at CERN for the LHC – combination of a Wall Current Monitor and a Beam Current Transformer
  - Insensitive to beam position
  - Installation without breaking the vacuum
  - Small magnetic cores (no worries with material homogeneity)
  - Capable of resolving the LHC bunch



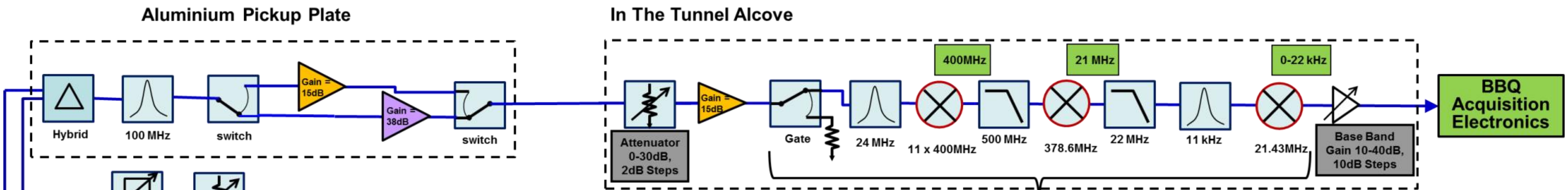


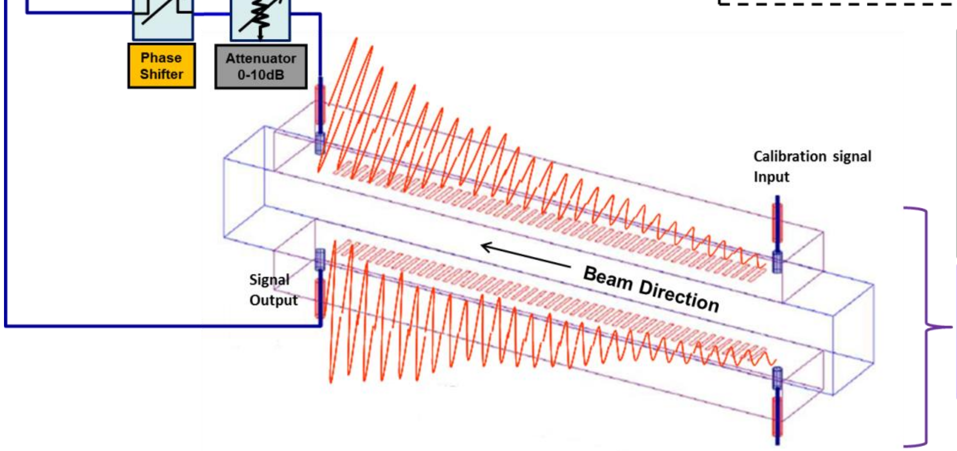




Courtesy Marek Gasior, Michał Krupa

LHC Schottky System 2010



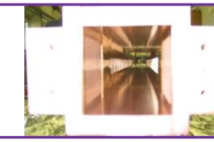


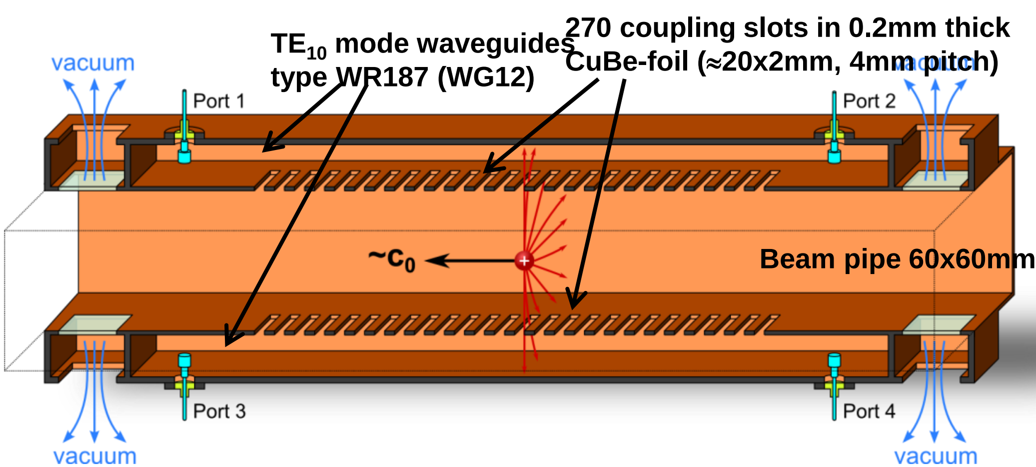
Triple down-mixing scheme to Base Band

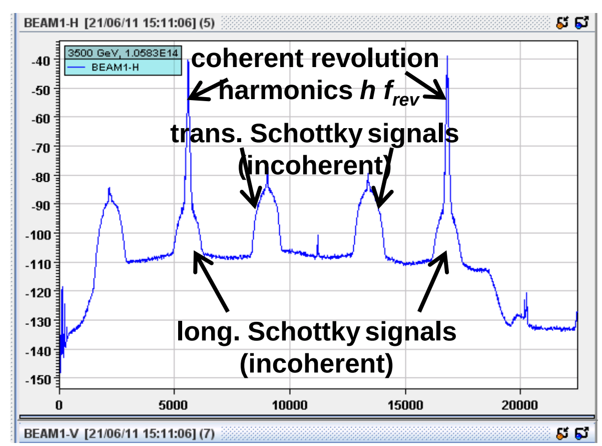
- Successive filtering from bandwidth of 100MHz to 11kHz
- Capable of Bunch by Bunch Measurement thanks to the 25ns Gate.
- Gate reduces noise theoretically about 30dB.
  Measurements are made using a 2x25ns = 50ns Gate to be sure we get all the signal from one bunch with the current 50ns spacing used for proton physics.

Slotted waveguide Structure

- High Sensitivity Pickup Structures operating at 4.8GHz
- Amplification of the signal for single bunch
- Pickup transverse sensitivity ~ 200MHz







Motivation for Schottky Signal Monitoring: Beam Parameter Characterization

- **The Schottky signals allow to characterize some transverse beam parameters in a non-invasive way:**
  - **Incoherent Tune**

    $$q = \frac{1}{2} + \frac{f_2 - f_1}{2 f_{rev}}$$

  - **Momentum spread**

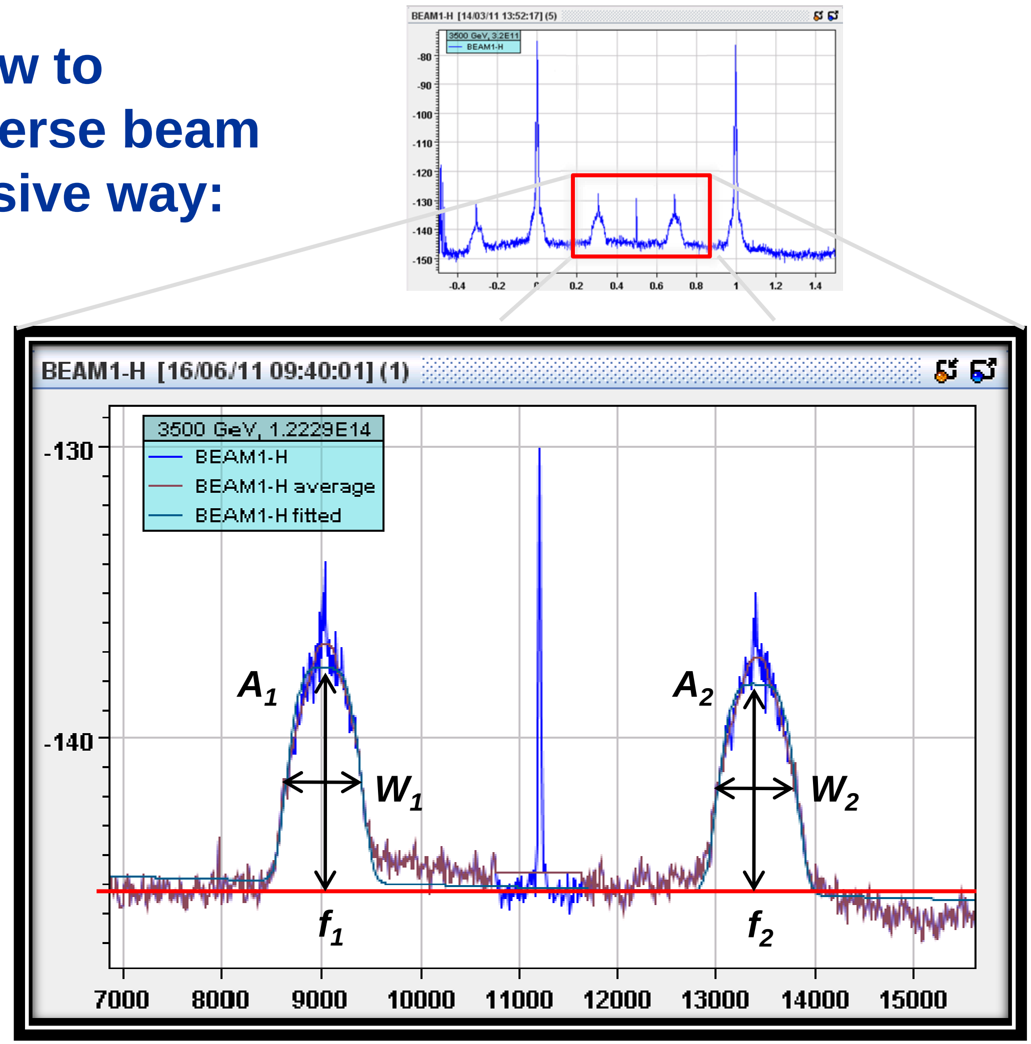
    $$\frac{\Delta p}{p} = \frac{1}{\eta} \frac{W_1 + W_2}{2 h f_{rev}}$$

  - **Chromaticity**

    $$\xi \propto \frac{W_1 - W_2}{W_1 + W_2}$$

  - **Emittance**

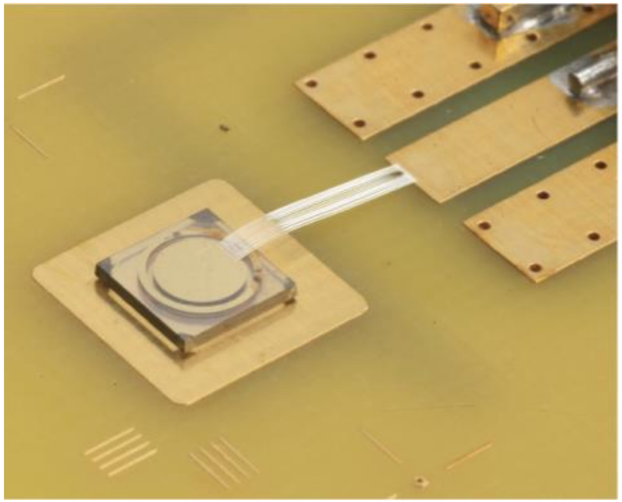
    $$\varepsilon \propto A_1 W_1 + A_2 W_2$$

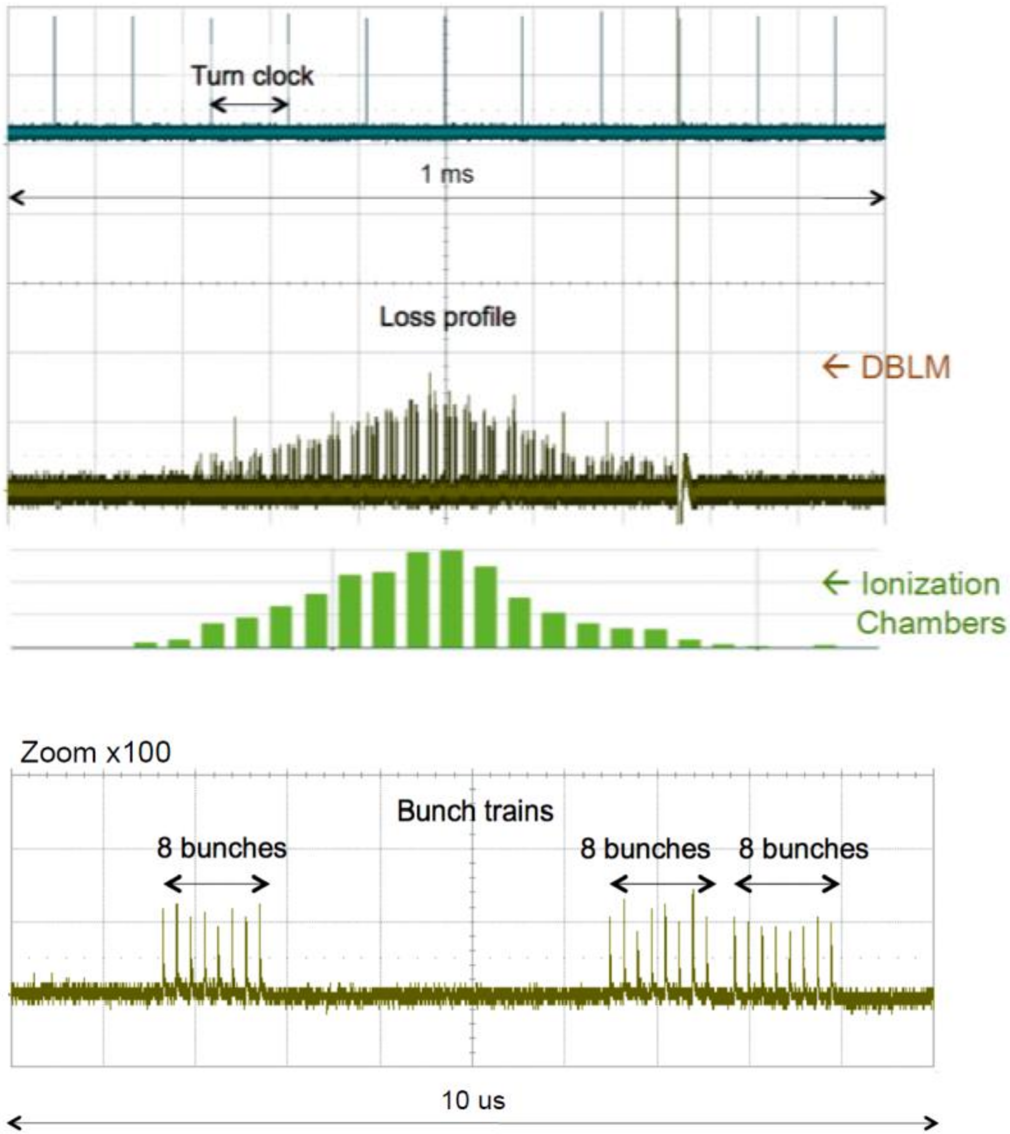


Zoom of the LHC proton Schottky signals (B1H, stable beam)

Diamond Detectors

- Fast and sensitive
- Small and radiation hard
- Used in LHC to distinguish bunch by bunch losses
- Dynamic range of monitor: 10^9
- Temporal resolution: few ns





Diamond: arrival time histogram during ramp

- 50 ns bunch spacing
- Loss signal at 25 ns is from opposite beam (“cross talk”)
  → sub 25 ns resolution required to resolve

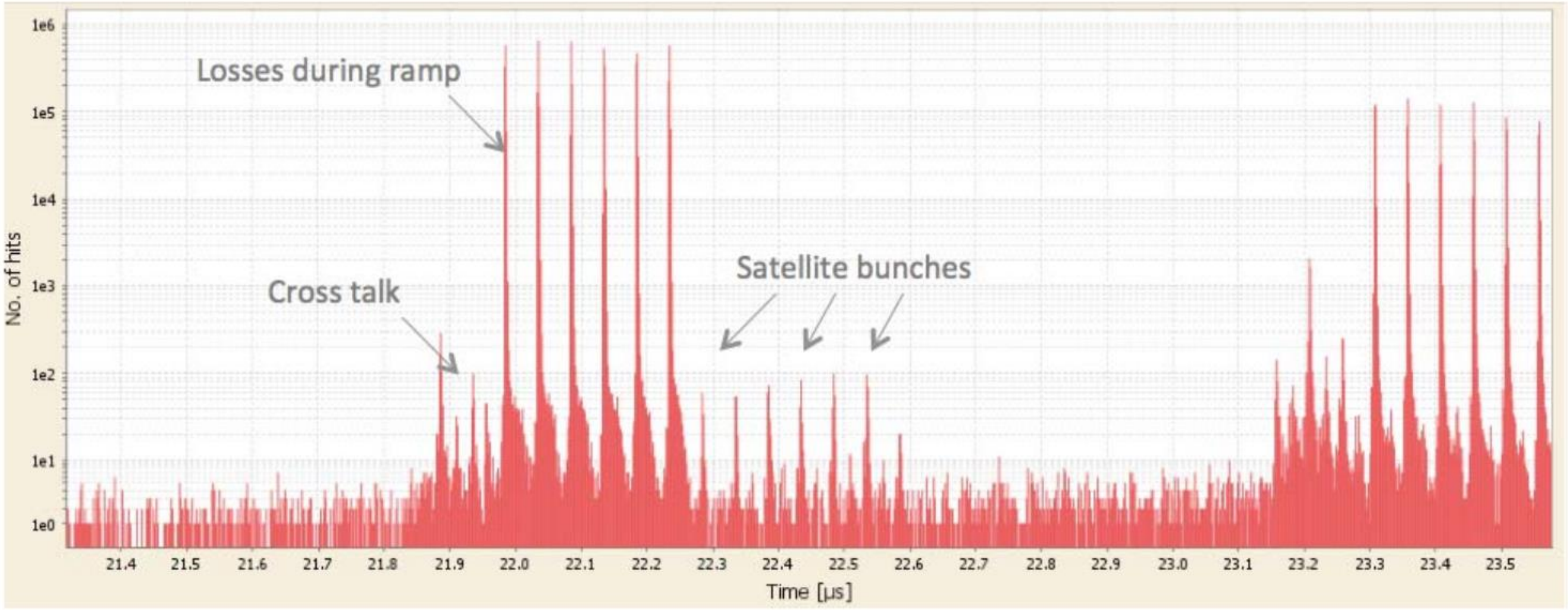


Figure 12: Losses during ramp.

Courtesy B. Dehning

Transverse Profile Measurements – Wire Scanners

	Wire speed	**Number of equipment**	**Dynamic range**	**Absolute accuracy** on emittance	**spatial resolution**	**Meas. range in Δx and Δy**	Bunch selection
PSB	rotational 15 m/s	1 H / ring 1 V / ring	100	20%	200µm	calibrated to +/- 5 cm	Could be made b-p-b ?
PS	rotational 15 m/s	3 H 2 V	100	20%	200µm	calibrated to +/- 5 cm	Could be made b-p-b ?
SPS	rotational 6 m/s	3 H 3 V	100	20%	200µm	+/- 5 cm	Bunch-per-bunch
	Linear 1/0.6 m/s	2 H 2 V	100	20%	50µm	~ +/- 4 cm	Bunch-per-bunch
Future SPS 2014	rot. 20 m/s	1 V	10^4 (spec)	< 10%	<10 µm	+/- 4 cm (full aperture)	Bunch-per-bunch
LHC	linear 1 m/s	1 H / ring 1 V / ring + 2 dev./ring	100	2013: 10-50% 2014: 10%	50µm	Full aperture	Bunch-per-bunch

- It typically takes a few 100 turns for one profile (e.g. PSB ~600 turns)
- LS1: systematic simulation study to improve WS accuracy

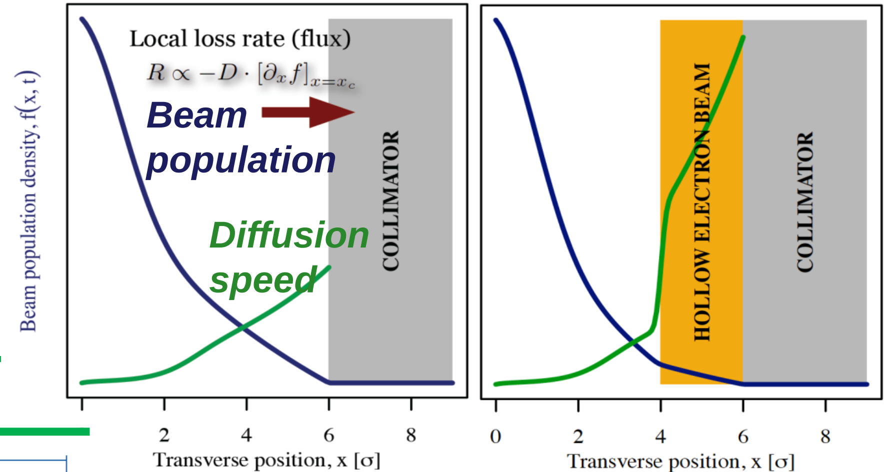
Transverse Profile Measurements - others

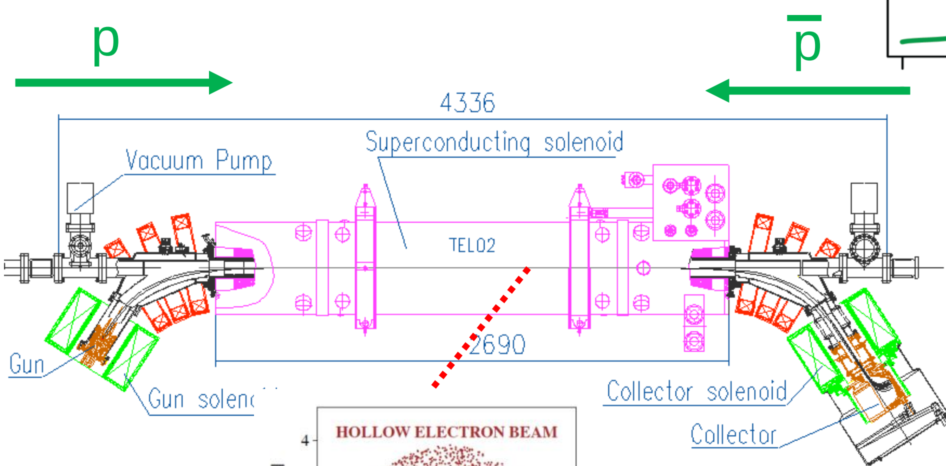
- Relative measurements, they need to be calibrated against the wire scanners

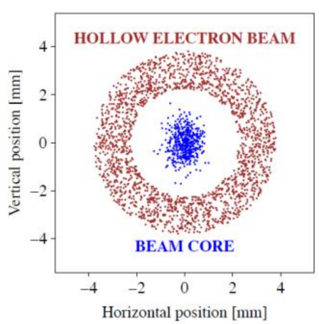
		Number of equipment	Dynamic range	Absolute accuracy on beam size measurement (after cross calibration)	relative accuracy emittance / beam size	spatial resolution	measurement rate	Bunch selection
SPS Synch. 2014 (refurbished)	Only above 300GeV	1	200 or 10^5 by changing attenuation	30% on emittance – hope to improve	10%/5% (same setting, 2 bunches in the machine for example)	~50µm (expected)	10Hz (flexile gating time width)	72 bunches – 1 PS batch
LHC Synchrotron Light	BSRT	1 / beam	200 or 10^5 by changing attenuation	30% on emittance – hope to improve	10%/5%	50µm	10Hz (flexile gating time width)	Bunch-per-bunch
SPS 2015	IPM	2: H,V	10^3	20%	5% / 2.5%	100µm	10 bunches in 0.1 s	Sum of all beam, maybe indiv. bunches)
LHC 2015	IPM	2 / beam	10^3	20%	5% / 2.5%	100µm	10 bunches in 0.1 s	

Beam Halo Mitigation: Hollow E-Lens

- Halo cleaning by electron lens demonstrated at Tevatron.
  - Soft scrapper
  - No material damage
  - Tunable strength – diffusion speed





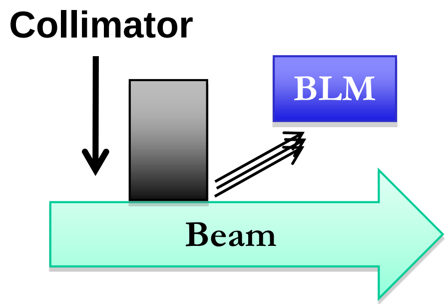


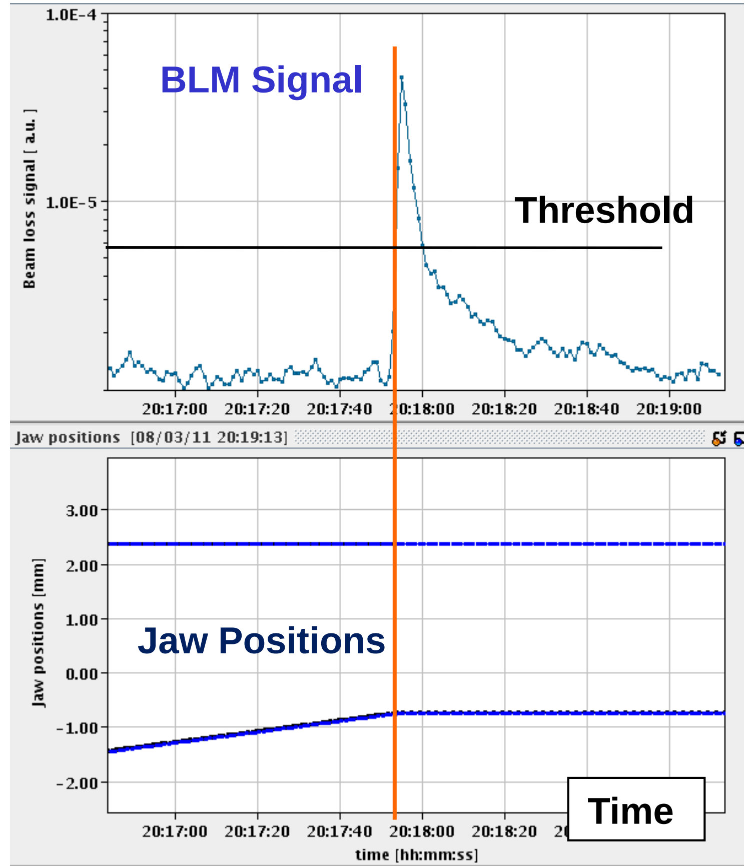
- **Such a lens is considered as option for HL-LHC (CERN_LARP collaboration)**

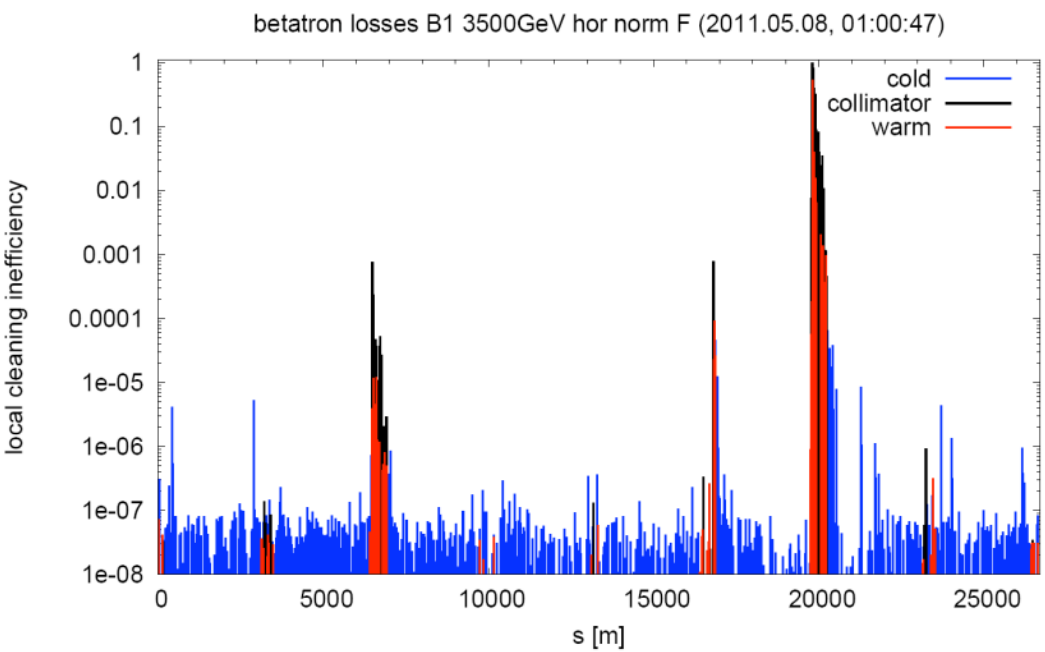
Stancari et al., Phys. Rev. Let. 107, 084802

Set-up and validation of collimation performance

- Find the beam center with each collimator jaw by stepping the jaw towards the beam and observing the BLM signal





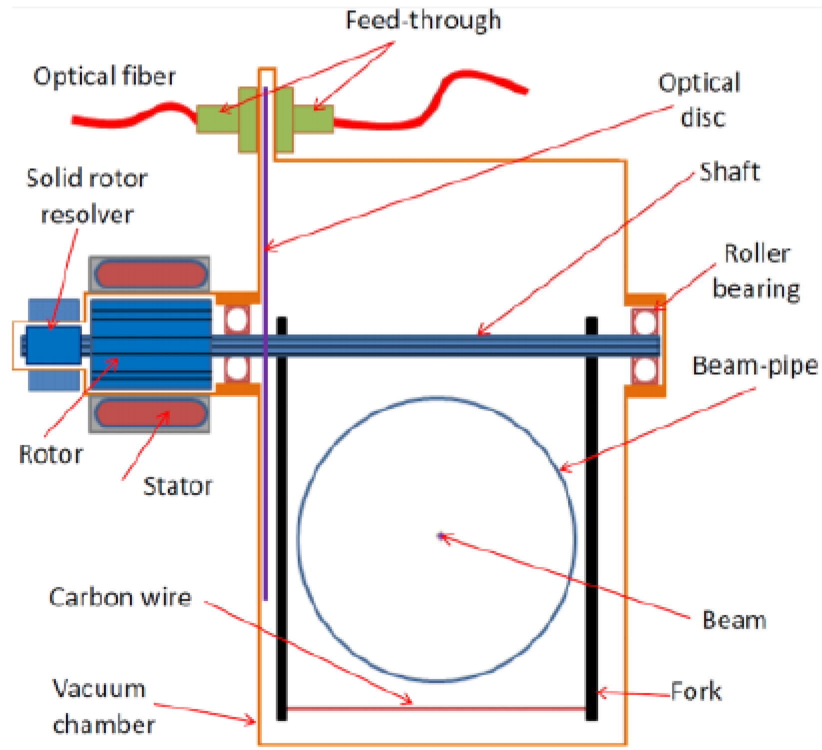


‘loss map’: losses along the ring normalized to the losses at the primary collimator: performance verification

New CERN Wire Scanner Development

Design Goals:

- Spatial resolution of few µm (using high resolution angular position sensor)
- Dynamic range: 10^4
- Minimize fork and wire deformations



- Solution to be found for impedance and RF heating
  - tank and fork geometry
  - **damping by loading with ferrite**
  - extracting power with **multi-mode coupler**
  - Current Wire Scanners at CERN: Dynamic range 100; accuracy 5-10%; spatial resolution 50 µm (linear type) and 200 µm (rotational)

B. Dehning