CERN

Proposal for PS Beam Gas Ionization monitor

Mariusz Sapinski, Oliver Keller, Bernd Dehning

With input from: Simone Gilardoni, Django Manglunki, Dominique Bodart, Rende Steerenberg, Jose Ferreira, Heiko Damerau and colleagues from GSI, BNL, Fermilab and J-PARC

BI technical board

May 15th, 2014

Outlook

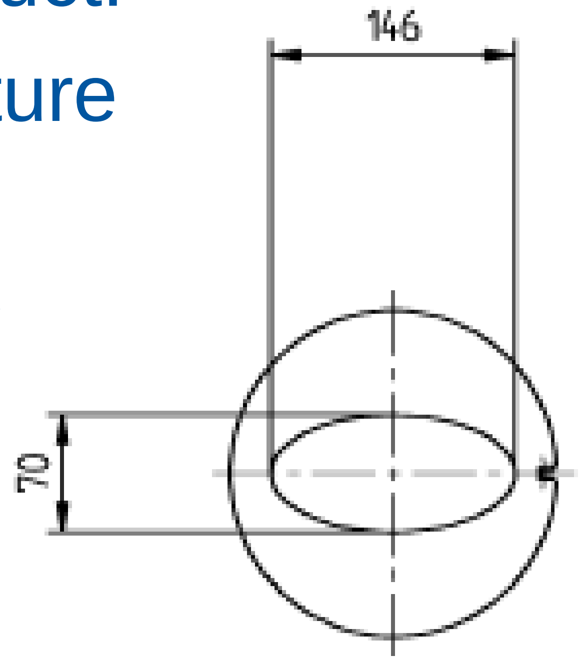
1. OP specification
2. Post-LS1 LHC beams in PS:
   - Expected beam sizes and dispersion issue
   - Wire sublimation in wire scanner
3. Location:
   - Rest gas pressure
   - Radiation levels
4. Electron rate estimation
5. HV cage – overview of existing solutions
   - HV scheme
6. Calibration and synchronization with beam
7. Magnets
8. Planning

Initial considerations

Because of vacuum chamber shape horizontal prototype is simpler to construct:

- Magnets with smaller aperture
- Simpler HV cage

Therefore most of initial study done for horizontal monitor.



Basic specification (OP)

- Typical beam size: σ=0.5-5 mm (LHC beams), cover ~ 5 cm
- maximum 72 bunches, 25 ns bunch spacing
- 10^{12} protons per bunch, 10^{8} Pb^{54+}ions per bunch
- bunch properties change during cycle (splitting, merging)
- **Normal mode:**

continuous bunch-by-bunch measurement during cycle - 0.1-1 kHz

- **Burst more: turn-by-turn measurements at chosen moment of the**

cycle (for about 5000 turns) – 360,kprofiles, can we do it?

- Independent power supplies and data lines for H/V monitors,
- cycle-dependent E and B drift fields.
- **Main use: qualification of LHC beams**

Post-LS1 LHC beams in PS

A few examples, for a complete lists: EDMS 1296306, September 2013

β_H=12m

Beam		N (10^{11})	$\varepsilon_{x,y}$ [µm]	E_{Kin} [GeV]	B_l [ns]	$\Delta p/p$ (10^{-3})	$\sigma_{y,x}$ [mm]
Standard 50ns	inj	**11.9**	**1.48**	**1.4**	**180**	**0.9**	**2.8/3.5**
	extraction	1.89	1.55	25	3	1.5	0.82/**3.7**
Standard 25 ns	inj	16.84	2.25	1.4	180	0.9	3.3/**3.9**
	extraction	**1.33**	**2.36**	**25**	**3**	**1.5**	**1.0/3.7**
LIU 50 ns	inj	18.95	1.69	2	205	1.0	2.55/**3.5**
	extraction	3.0	1.77	25	3	1.5	0.86/**3.7**
LIU 25 ns	inj	28.07	1.63	2	205	1.5	2.5/**4.4**
	extraction	2.22	1.71	25	3	1.5	0.84/**3.7**
HL-LHC BCMS 25ns		16.25	1.8	2	135	1.1	2.6/**3.7**
HL-LHC BCMS 50ns		4.09	2.27	25	3	1.5	1.0/**2.8**

4+2 b@inj

In horizontal plane the beam size is dispersion-dominated.

Post-LS1 LHC beams in PS - dispersion

For example:

Beam	N (10^{11})	$\varepsilon_{x,y}$ [μm]	E_{Kin} [GeV]	B_l [ns]	Δp/p (10^{-3})	$\sigma_{y,x}$ [mm] β_H=12m
LIU 50 ns	18.95	1.69	2	205	1.0	2.55/**3.5**
	3.0	1.77	25	3	1.5	0.86/**3.7**

Assuming emittance blow by 10% at FT: 1.77 μm → 1.95 μm

Corresponding beam size change: 3.70 mm → 3.71 mm – not measurable

Important:

- Very good knowledge of optics, dispersion and dp/p
- To measure dispersion: beam position close to BGI (PU or BGI itself?)
- Find location with β_H=22m -> 10-20% emittance increase could be measured

Horizontal wire scanner measurements are still useful for operation.

Post-LS1 LHC beams in PS – WS damage?

Beam	N (10^{11})	$\varepsilon_{x,y}$ [μm]	B_l [ns]	$\sigma_{y,x}$ [mm]	N_{bunch}	$n_{ch}=NN_{bunch}d/vt\sigma_y$
Standard 50 ns inj	11.9	1.48	180	2.7/**3.4**	6	$1.4\cdot10^{12}$
extraction	1.89	1.55	3	0.81/**3.7**	36	$4.5\cdot10^{12}$
Standard 25 ns inj	16.84	2.25	180	3.3/**3.9**	6	$1.6\cdot10^{12}$
extraction	1.33	2.36	3	1.0/**3.7**	72	$5.1\cdot10^{12}$
LIU 50 ns inj	18.95	1.69	205	2.55/**3.5**	6	$2.4\cdot10^{12}$
extraction	3.0	1.77	3	0.86/**3.7**	36	$6.6\cdot10^{12}$
LIU 25 ns inj	28.07	1.63	205	2.5/**4.4**	3	$3.6\cdot10^{12}$
extraction	2.22	1.71	3	0.84/**3.7**	72	$1.0\cdot10^{13}$

From SPS experiments the safe value for wire is about **$5\cdot10^{12}$ charges/mm**.
(done for 30 μm SPS/LHC wire, no experience with multi-filament wire).

Wire scanners limits in PS

- Currently wire scanners are the only devices measuring beam emittance in PS.
- Scanning at FT for after-LS1 beams may lead to wire sublimation and in consequence to breakage.
- BGI allows for continuous observation during the cycle.

Post-LS1 LHC ion beams in PS

Based on EDMS-1311644

for β=12m

Beam	N (10^8) ions	$\varepsilon_{x,y}$ [μm]	E_{kin} [GeV]	$\beta_{rel}\gamma$	B_l [ns]	Δp/p (10^{-3})	$\sigma_{y,x}$ [mm]
injection	3	0.7	15.02	0.4	200	1.2	4.6/**5.3**
extraction	2.5	1.0	1227	7.4	4	1.1	1.3/**2.9**

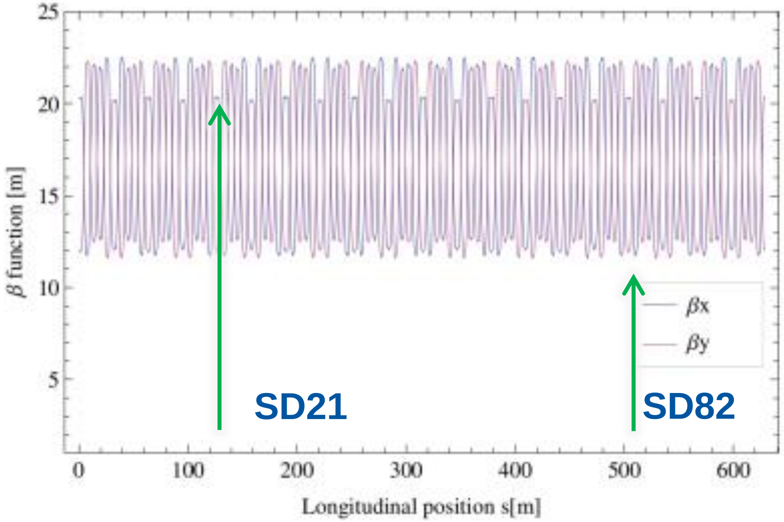
Revolution frequency:

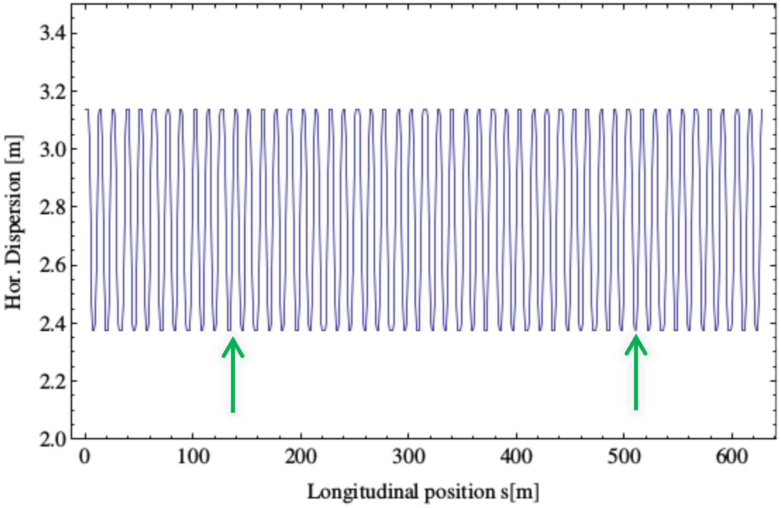
- Injection: 5.63 μs
- Extraction: 2.12 μs

Only Pb54+ beams are foreseen (LHC), but some experiments consider Ar, O, N.

Location - optics

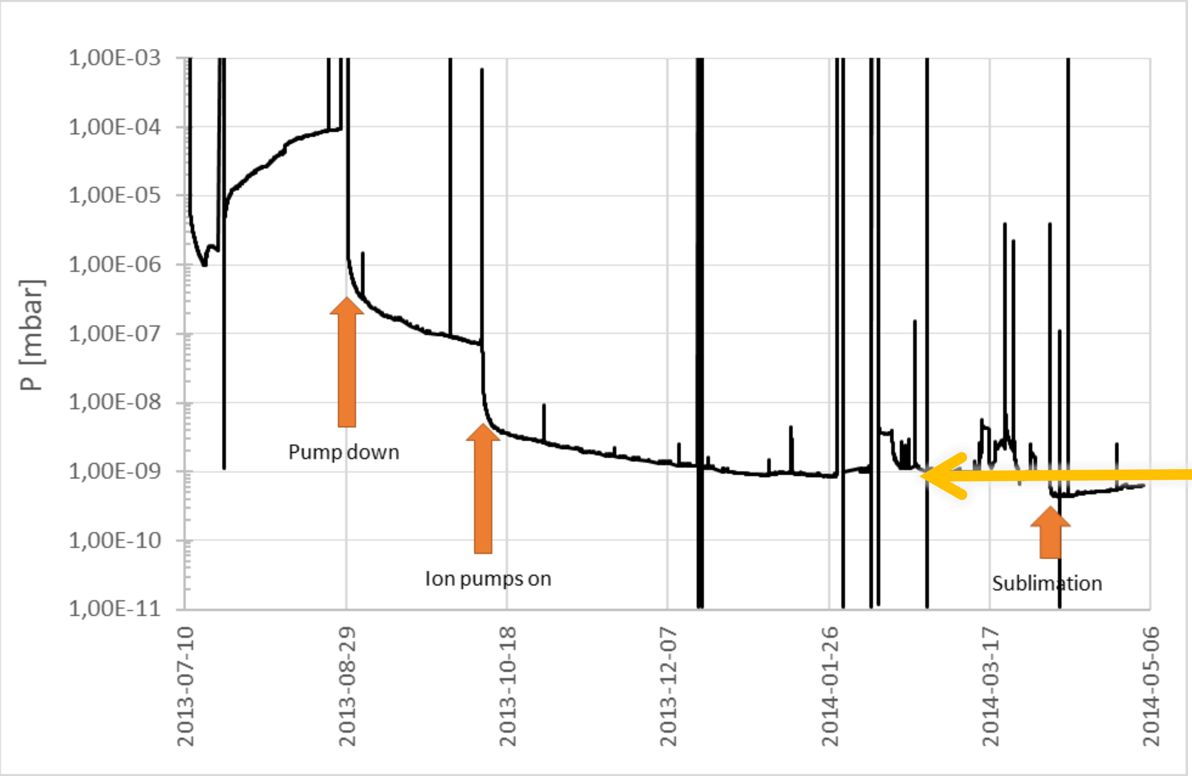
- Not many sections available.
- Considered: SD31, 33, 35 - large radiation/activation.
- SD82 dcum=510-511 m
- β_x=12m, D=2.4m, B_y=22m
- Another option: SD21, but only if CT kicker removed. Large β_x decreases impact of dispersion (dcum 127-128m).
- Other locations still possible – study ongoing.





Rest gas pressure evolution

Vacuum in sector 82 is very good.



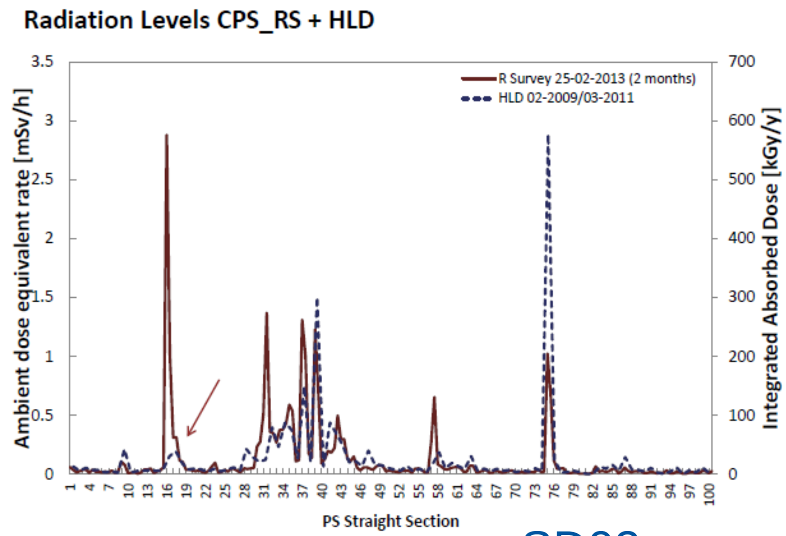
Do we need a gas injection system?

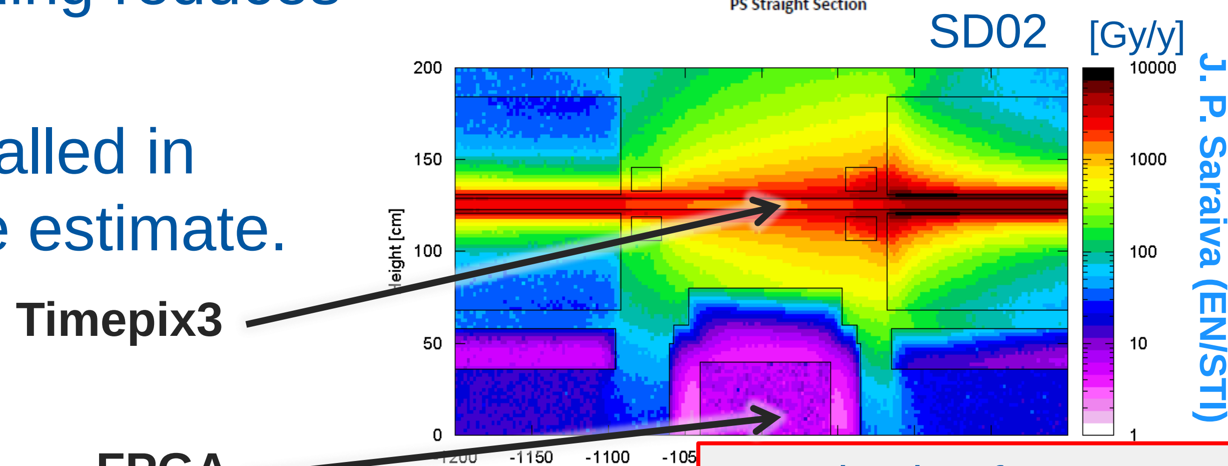
10^{-9} mbar

Courtesy of J. Ferreira

Radiation

- The chip is radiation tolerant, FPGA needs shielding.
- FPGA needs to be ~ 1-2m from chip
- FLUKA: shielding reduces dose by 10.
- Radmons installed in SD82 for dose estimate.





Reduction factor: **~10**
with 40 cm of iron shielding

Location and radmons (prep for installation)

Estimation of ionization rate (I)

- Ionization cross-section:

$$\sigma_{ion} = Z^2 \left(\frac{h}{2\pi mc}\right)^2 \beta^{-2}\left(M^2 x(\beta) + C\right)$$

- *M*,*C* – depend on gas type, here assuming Neon/H_2
- Typical cross-sections:

particle	p	p	Pb54+	Pb54+
Kin. energy [GeV]	1.4	25	15.02	1227
Cross-section [Mbarn]	0.44 0.19	0.56 0.23	5600 2650	1350 570

The cross-section estimations based on Geant4 are 2-3 times lower (for protons) and even less for Pb54+.
In the following optimistic Ne cross-sections are assumed.

Estimation of ionization rate (II)

- Gas pressure: 10^{-9} mbar
- Detector length: d=15 mm

$$n_e = d\,\sigma_{ion} N_b\, p N_A / RT$$

beam	p (std, 50ns)	p (std, 25 ns)	Pb54+	Pb54+
E_{kin} [GeV]	1.4	25	15.02	1227
Cross-section σ_{ion}[Mbarn]	0.44	0.56	5600	1350
Bunch population N_b	$12 \cdot 10^{11}$ (in 180 ns)	$1.3 \cdot 10^{11}$ (in 4 ns)	$3 \cdot 10^{8}$ ions (in 200 ns)	$2.5 \cdot 10^{8}$ ions (in 4 ns)
Electrons per bunch n_e	190 (~10% stat error on emittance)	26 (~28% stat error on emittance)	610 (~6% stat error on emittance)	120 (~13% stat error on emittance)

Without gas injection statistical errors on emittance (without dispersion) when taking a bunch snapshot are very large!

Signal rate

Important for the readout chip (see Oliver's presentation)

beam	p (std, 50ns)	p (std, 25ns)	Pb54+	Pb54+
E_{kin} [GeV]	1.4	25	15.02	1227
Bunch population	$12\cdot10^{11}$ (in 180 ns)	$1.3\cdot10^{11}$ (in 4 ns)	$3\cdot10^{8}$ ions (in 200 ns)	$2.5\cdot10^{8}$ ions (in 4 ns)
No of bunches	6	72	2	2
Electrons per bunch	190	26	610	120
Per chip (inside bunch/averaged per turn)	1 GHz/ 0.5 GHz	6.5 GHz/ 0.9 GHz	3 GHz/ 0.2 GHz	30 GHz/ 0.1 GHz
Per pixel (inside bunch/averaged per turn)	20 kHz/ 10 kHz	130 kHz/ 18 kHz	49 kHz/ 3.4 kHz	1.6 MHz/ 5.6 kHz

Signal rate regulation

Need to regulate the signal because it can pile-up in analog (>2 MHz) front end. Can regulate:

- Gas pressure – slow
- Gas temperature (?)
- Gas type – not feasible (?)
- Accelerating voltage – detection efficiency
- HV gating (fast HV switch)
- Pixel masking
- Pixel thresholds

HV cage

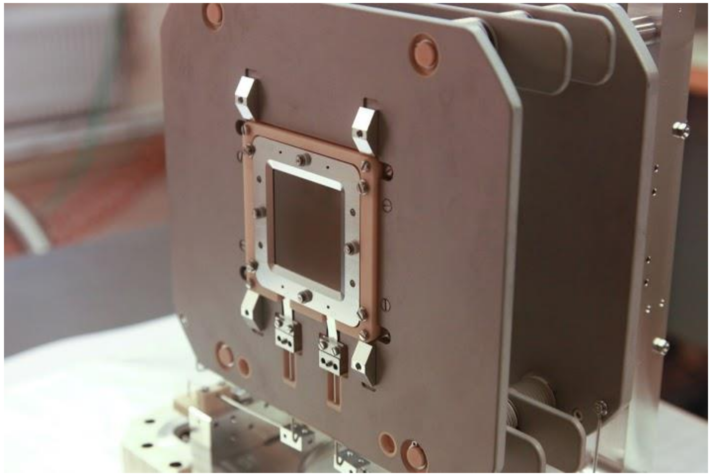
- Provide uniform electric field in the area of the detector
- Low impedance – not critical in PS
- In Fermilab they used side electrodes to “clean” electron cloud (gate-off)

HV cage – examples (1)

- CERN SPS/LHC:

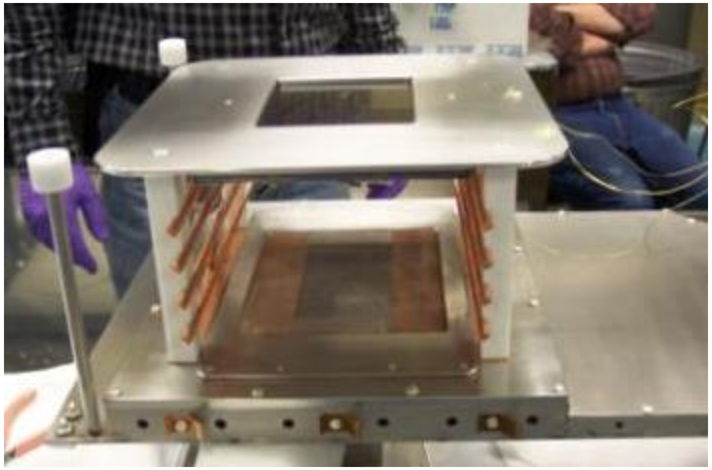
No bbb (slow phosphor and low signal per bunch), optical readout

Beam sigma: 0.5-0.1 mm

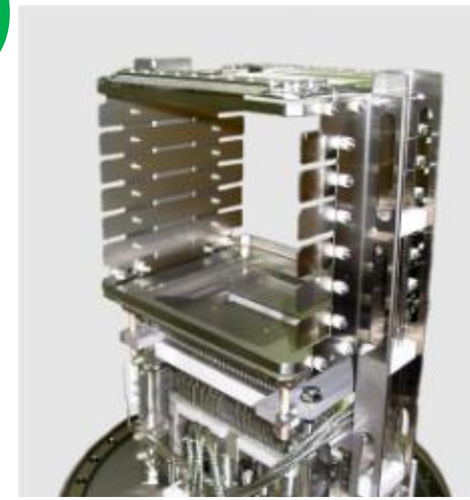


- FNAL Mark III:

bbb, tbt, bunch spacing: 120ns(p-pbar) and 396ns, beam sigma:0.6-4.5mm, bunch intensity: 2.5e11



HV cage – examples (2)

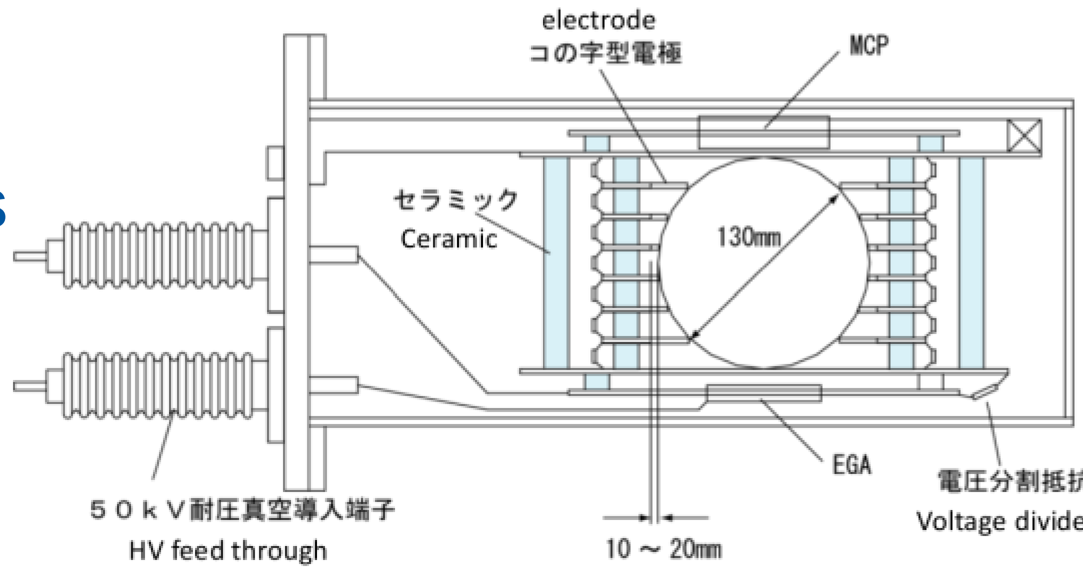


- <u>GSI:</u> large low energy ion beams

Models: SIS18 (anodes),
ESR (optical)

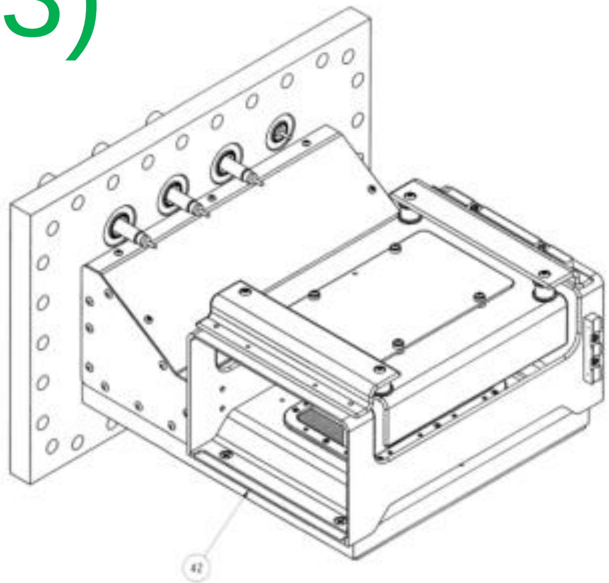
- <u>J-PARC (MR):</u>

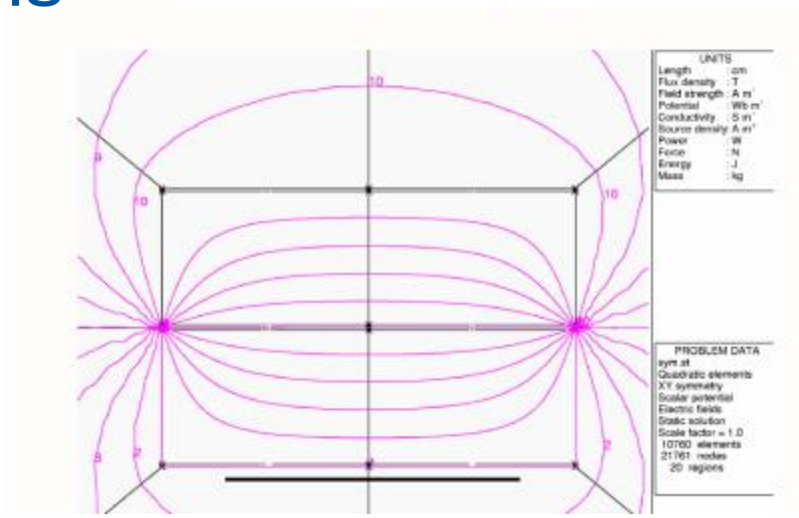
bbb, tbt,
bunch spacing: 300 ns
beam sigma: 10 mm
bunch intensity: 5e12
HV 50 kV,
electrons or ions



HV cage – examples (3)

- BNL: bbb & tbt,
  bunch spacing: 100 ns,
  beam sigma: 10-3 mm,
  bunch intensity:
  1e9 ions, 2e11 protons





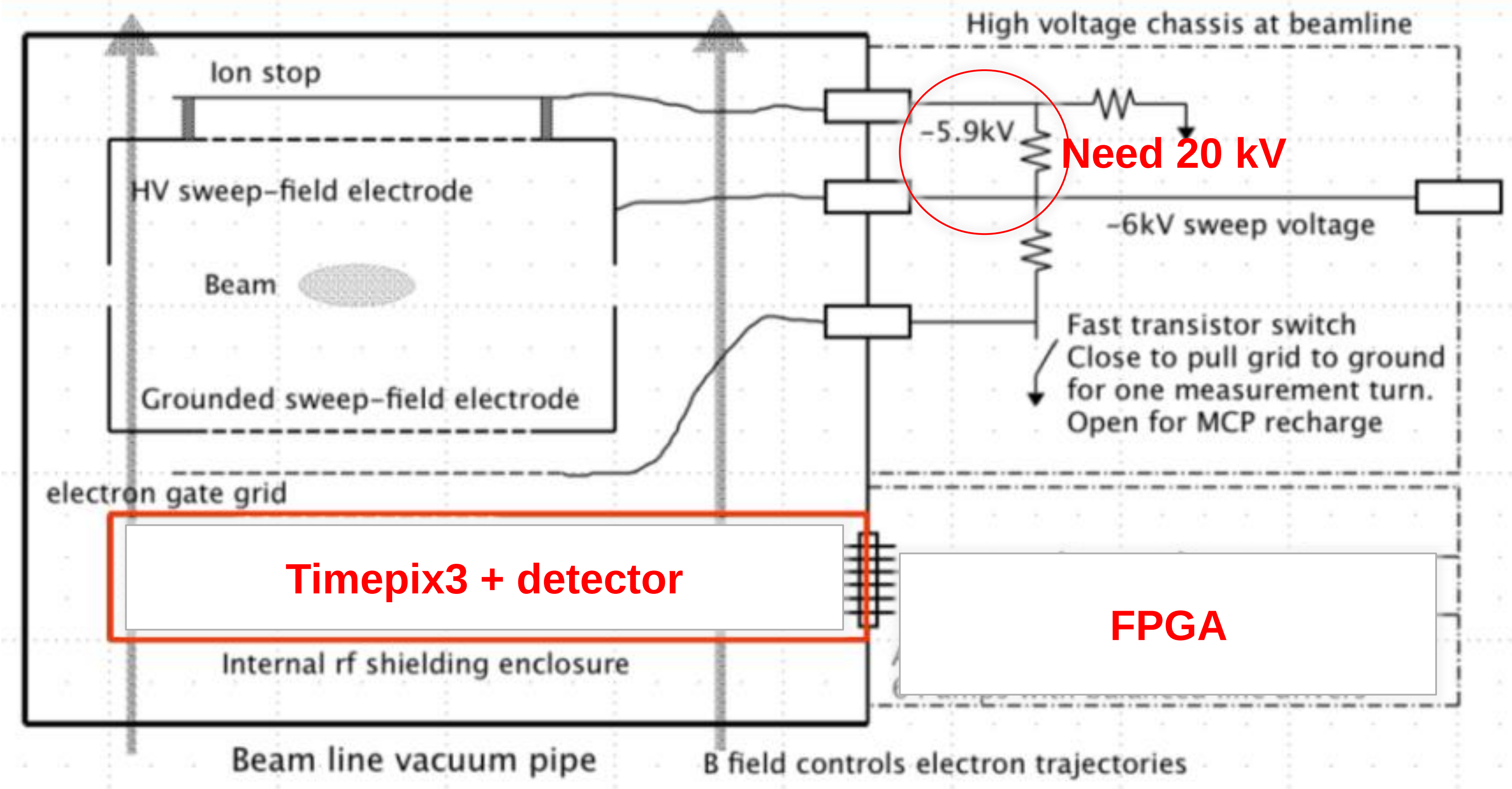
HV cages – comparison

BGI	Aperture [mm]	Width [mm]	Length [mm]	Extraction voltage [kV]
FNAL mark3	63	94	158	10-30
J-PARC (MR)	130	130	120	50
BNL	**87**	**140**	**192**	**10**
GSI	170	170	160	12
PS hor	**70**	**146**	**tbd**	**20**
PS ver	**146**	**70**	**tbd**	**20**

We find BNL solution interesting:

- Simple, tested, nice solutions like honeycomb for RF shielding.
- Size close to PS horizontal monitor.
- EM simulations done long time ago and not well documented
  -> be done soon
- Complete set of tech drawings at CERN, modifications necessary

HV scheme



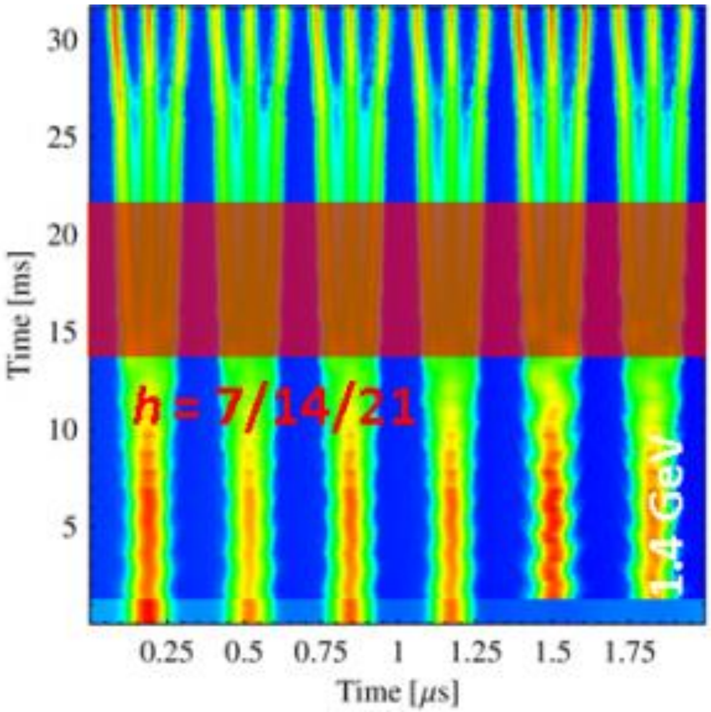
High voltage chassis at beamline
Ion stop
-5.9kV
Need 20 kV
HV sweep-field electrode
-6kV sweep voltage
Beam
Fast transistor switch
Close to pull grid to ground
for one measurement turn.
Open for MCP recharge
Grounded sweep-field electrode
electron gate grid
Timepix3 + detector
FPGA
Internal rf shielding enclosure
Beam line vacuum pipe
B field controls electron trajectories

Calibration

- Pixel scale calibration – not needed.
- Pixel gain calibration – each pixel has individual gain control, dead pixels can be masked.
- Calibration source? Or beam-based calibration?
- Start with calibration by gaussian fit (see presentation M.Minty at 9th Ditanet Workshop - April 2013).

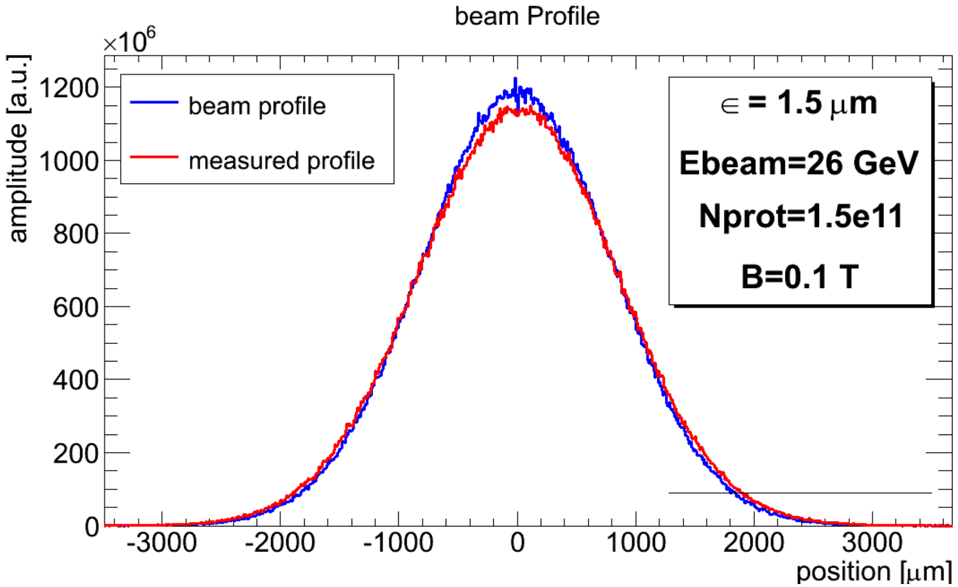
Synchronization with machine

1. Use machine synchronous clock tref with cable length compensation.
2. Use similar signal processing from PU as in trajectory measurement system by J. Belleman.



Magnets

- Magnet design will take as input the shape of vacuum chamber (Dominique Bodart).
- Good-field region: ~5 cm
- Iron-yoke type corrector magnets of 2 types (H,V)
- What field do we need (lesson from LHC)?



by Dominik Vilsmeier

No dispersion
(worst case scenario)

Field needed:

B=0.15 – 0.2 T

Surface electronics

- Building 368
- We will need a rack for PC (data buffering), HV power supplies, machine clock synchronization, slow control

Next steps

- Test: Timepix1 + 100 um detector + electron source in vacuum – proof of principle.
- Assembly Timepix3 (FPGA evaluation board Chip available soon), start programing FPGA.
- ECR needed soon.
- Electric field simulation and HV cage design.
- Detector assembly design (scale cooling solution from Gigatracker?).
- Design new FPGA board (rad-hard elements).
- End of 2015: prototype in the machine.

Conclusions

- **Continuous monitoring of beam emittance in PS can be achieved by BGI monitor with fast silicon pixel detector.**
- No existing BGI is measuring 25 ns beams bunch-by-bunch.
- See next presentation for novel readout system proposal.
- **Proposed chip will withstand radiation**, but FPGA is fragile.
- Enough electrons to measure bbb averaged over 0.1 ms.
- Gas injection needed only in ‘per turn’ measurement.
- Staged development (start with one chip, foresee more).
- **HV cage solution could be adapted from BNL detector.**

Additional resources:

- TWiki:
  https://twiki.cern.ch/twiki/bin/viewauth/PSBGI/WebHome
- Presentation at LIU PS meeting on February 11th, 2014
- Presentation at BI-LIU review on October 3rd, 2013

SPARE SLIDES

Choice of measurement principle (I)

Light

Pros:

- Electrical isolation between detector (phosphor) and rest of the structure
- No signal feedthroughs
- Good resolution – small beams

Cons:

- Light extraction system (larger vacuum chamber and magnet aperture)
- Need of extraction window

Electrons/ions

Pros:

- Simpler construction in vacuum
- Smaller vacuum chamber needed

Cons:

- Electrical connections close to beam wakefields

Choice of measurement principle (II)

- Time to reach detector surface:
  electrons 2-3 ns, ions: 400 ns
- Use both: ions for cross-section estimation or signal level estimation to prepare HV?
- Ions have sense for machines with large bunch spacing (no need for magnet) and small bunch charge.
- Electrons – need for magnets.

LHC beams in PS

beam	SPS ftarget	TOF	EASTA	LHC 25 ns 72 bunches
		Injection		
Ek [GeV]	2.0	2.0	2.0	2.0/1.4
Bunch nrb	8	1	1	6
Charges/b	3.1E12	8E12	4E11	1.5E12
Bunch len [ns]	150	190	170	180
εH/V [μm rad]	7.6/5.4	9.2/7.8	1.5/1.5	1.5
		Extraction		
Ek [GeV]	14	20	24	26
Bunch nbr	420 (deb)	1	1	72
Charges/b	~5E10	8E12	3.8E11	1.25E11
Bunch len [ns]	5	50	debunched	4
εH/V [μm rad]	11/8	12/10	-	1.5

EDMS 1157752, document in work

Estimation of ionization rate (I)

- Ionization cross-section:

$$\sigma_{ion} = Z^2 \left(\frac{h}{2\pi mc}\right)^2 \beta^{-2}(M^2 x(\beta) + C)$$

- M,C – depend on gas type, here assuming Neon
- Typical cross-sections:

particle	p	p	Pb82+	Pb82+
Kin. energy [GeV]	1.4	25	15.02	1227
Cross-section [Mbarn]	0.44	0.56	3700	3300

The cross-section estimations based on Geant4 are 2-3 times lower.

Location

Potential issues

- E-cloud at end of the LHC 25 ns cycle (a few ms before extraction) – there is e-cloud monitor in PS
- Report of low-energy electrons “shielding” the silicon detector surface – need to experiment soon
- Smaller and standard flange (lesson from LHC vacuum problems, but lot of experience now)
- Rest gas temp measurement (?)