Measurements of gas bremsstrahlung radiation in the Sector 35 diagnostic beamline

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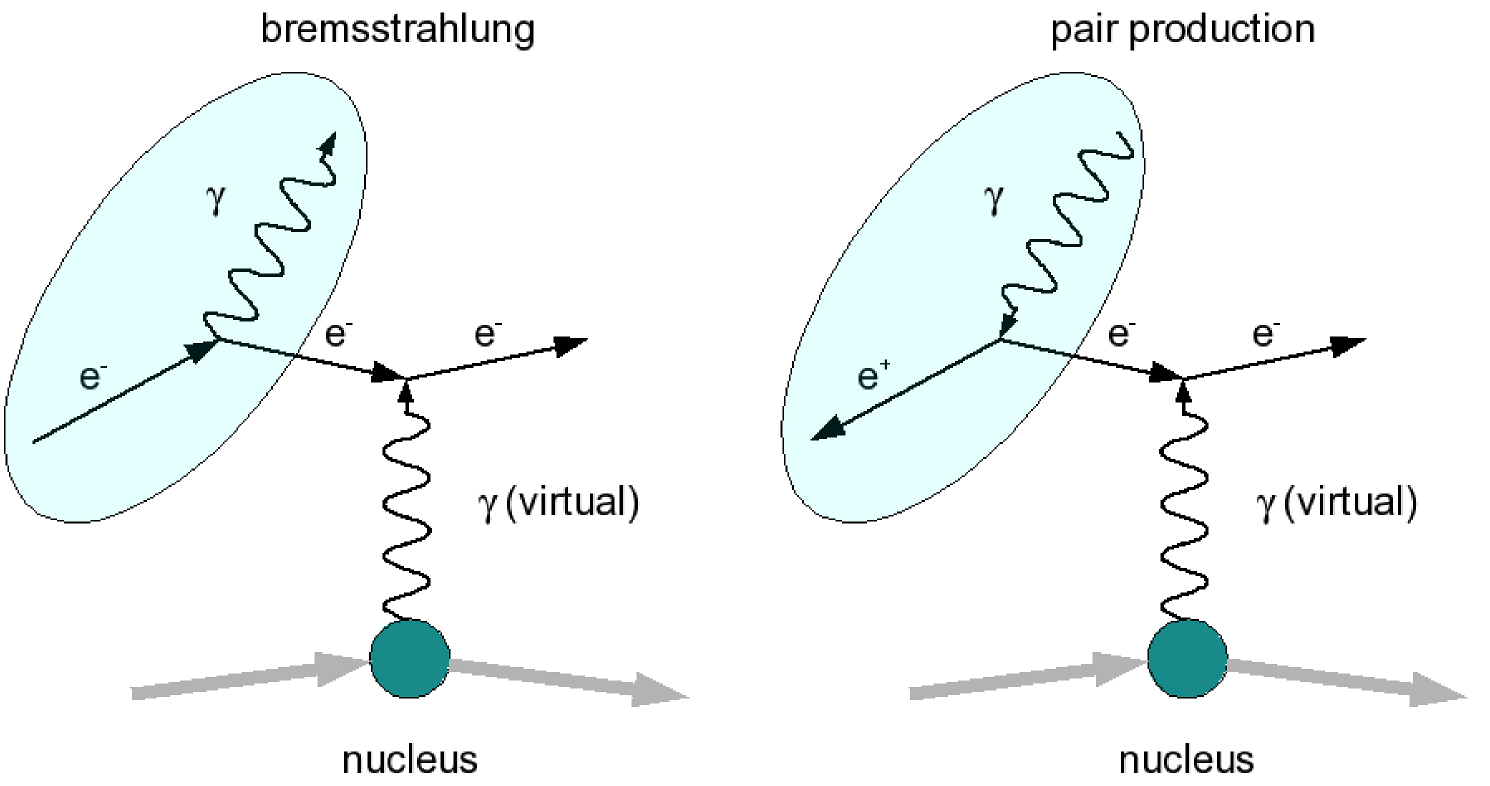
Bldg 401 A1100

Gas bremsstrahlung—what is it and why study it?

- Gas bremsstrahlung (GB) or “breaking radiation” refers to the high-energy photons created when 7-GeV electrons interact with the background gas in the SR vacuum chambers.
- In straight-sections used for IDs, the integrated target density can result in 10's of μWatts of GB power.
- The target density depends on pressure, length, and the chemical composition of the background gas (Z_{eff}).
- Though, relatively small in magnitude, this penetrating radiation creates a radiation hazard through the production of photoneutrons.
- The magnitude of the GB is an issue for the upgrade. Pressure in the straight sections varies with beam current through desorption and other mechanisms.

Gas Bremsstrahlung

Bremsstrahlung and pair-production are closely related processes. Both take place in an electromagnetic shower.



GB emission—using Fermi-Thomas model (potential defined density)

- number of photons per electron per unit length (Rossi):

$$F(k)dk = 4\alpha r_e^2 \frac{N_A}{A} Z(Z+1)\frac{dk}{k} f(\nu, Z)$$

- form factor for complete screening of the nucleus (Γ_{Ros}~0),

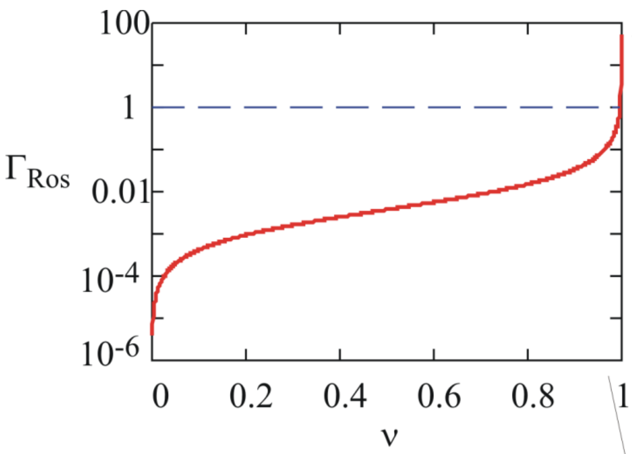
$$f_{cs}(\nu, Z) = \left[\nu^2 - \frac{4}{3}\nu + \frac{4}{3}\right]\ln\left(\frac{183}{Z^{1/3}}\right) + \frac{1}{9}(1-\nu)$$

- from a bare nucleus (no screening—no Z effect, Γ_{Ros}>>1))

$$f_{ns}(\nu, Z) = \left[\nu^2 - \frac{4}{3}\nu + \frac{4}{3}\right]\left(\ln\left(\frac{2T}{E_{eo}}\frac{(1-\nu)}{\nu}\right) - \frac{1}{2}\right)$$

where α is the fine structure constant, r_e the classical electron radius, N_A, Avagadro's number, A the atomic mass, Z atomic number, k photon energy and ν=k/(T+E_{eo}), where T is the kinetic energy E_{eo} and the rest mass energy of the electron

Screening factor determines scattering regime

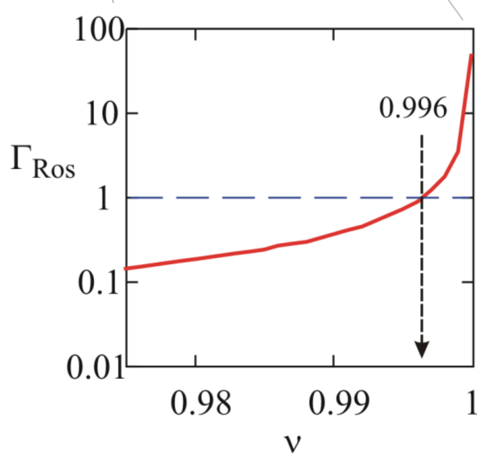


Z	ν_t ($\Gamma_{Ros}(\nu_t)=1$)
7.3	0.996
4.0	0.995
2.0	0.994

$$\Gamma_{Ros} = 100\frac{E_{eo}}{U}\frac{\nu}{1-\nu}Z^{1/3}$$

$$U = T + E_{eo}$$

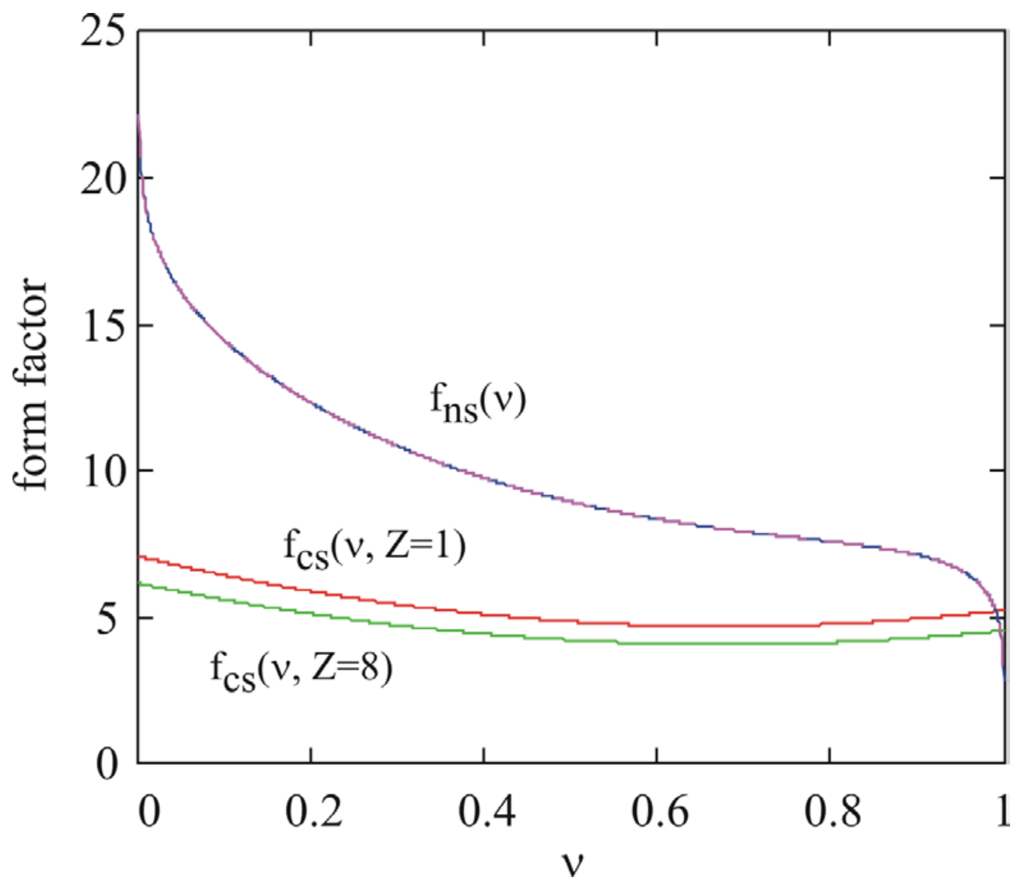
$$T = 7\ GeV$$



except for the highest energy photons, nuclei are always fully screened

GB form factor

Screening reduces the scattering cross section



Radiation considerations

—Initial calculations for radiation shielding in the hutches can be found in TB-7 and TB-20 (circa 1993-94).

- 7-GeV, 300 mA
- 1 nTorr of air (Z=7.3)
- straight section length of 15.38 m
- 0.46 μW/mA/nTorr

∴ at 100 mA, should expect ~ 46 μW/nTorr (assuming background gas is air)

Radiation considerations

Later measurements at APS found

1) hydrogen dominated the residual gas ($Z_{act}<Z_{air}$)
2) the background gas pressure depended on the beam current.

- LS-260—pressure observations
- LS-269—pressure measurements

In LS-260, gas composition is given for beam off and beam on conditions

- Chemical composition of the residual background gas differs from that of air.
- Variation in composition is noted depending on whether beam is present or not.

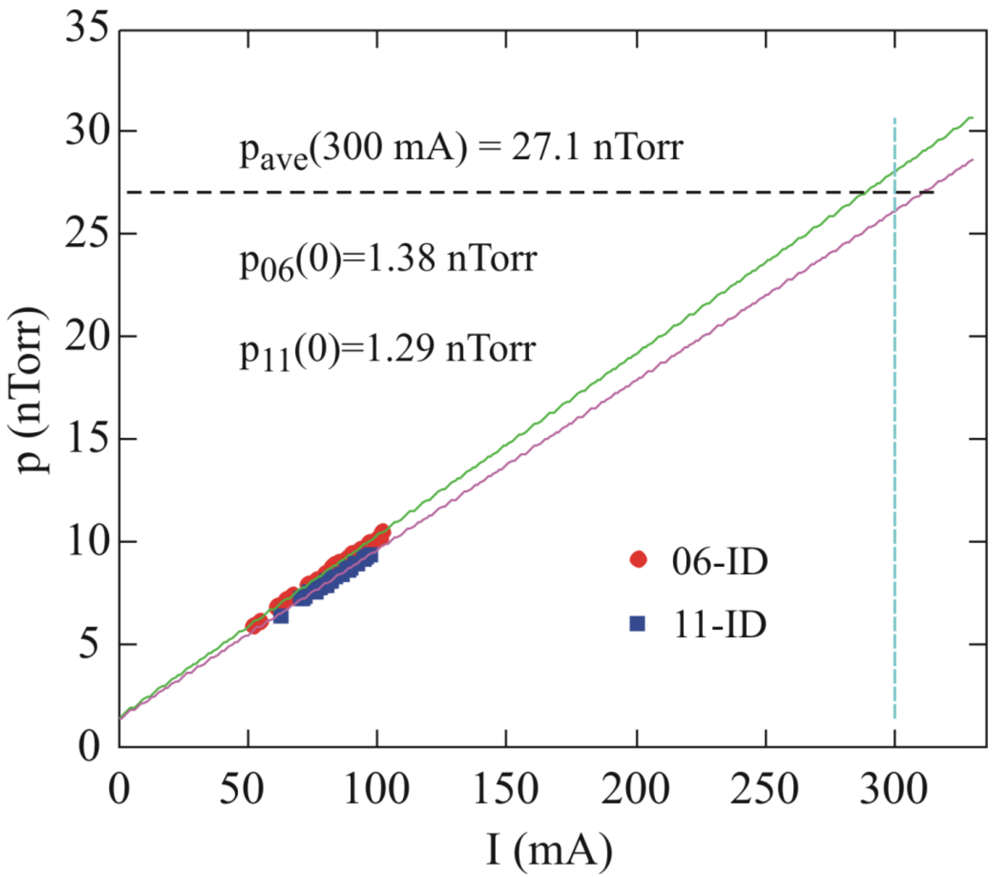
Mass No.	Residual gas compo-nent	Mole Fract. (%)		Weight Fract. (%)	
		Beam on	Beam off	Beam on	Beam off
2	H_2	70.1	73	15	17.6
12	C	0.88	0.48	1.1	0
16	CH_4	1.7	2.3	2.9	4.4
17	OH	0.75	0.97	1.4	2
18	H_2O	2.13	3.43	4.1	7.4
28	N_2/CO	19	15.7	57.1	53.1
40	Ar	0.3	0.31	1.3	1.5
44	CO_2	3.6	2.6	17.1	14

According to Avogadro's principle, in a gas, the mole (volume) fraction determines the effective Z. From the data above:

$Z_{eff,beam\ off}=2.31$ and $Z_{eff,beam\ on}=2.54$

Radiation considerations

for TB-54 calculations, extrapolated pressure from data presented in LS-269 (NIM-A 430)



Done to include pressure effects in the GB dose calculation (data taken from Tables 3 and 4 in LS-269).

Needless to say, this is a big extrapolation!

Radiation considerations

- In reality, to accurately determine the GB power, we must integrate over energy and space.
- The target density, ρL_{ss} represents the integrated density over the straight section length.

- stopping power: energy deposited / length
- equivalently this is the GB energy generated per unit length (MeV/cm/e)

$$\left.\frac{dT}{dx}\right|_{rad} = -4\alpha\, r_e^2 \frac{N_A}{A} Z(Z+1) T \int_0^1 \frac{d\nu}{\nu} f(\nu, Z)\rho$$

$$= -4\alpha\, r_e^2 \frac{N_A}{A} Z(Z+1)\left[\ln\left(\frac{183}{Z^{1/3}}\right) + \frac{1}{18}\right]\rho T$$

$$= -\frac{\rho T}{X_o}$$

$$X_o^{-1} = 4\alpha r_e^2 \frac{N_A}{A} Z(Z+1)\left[\ln\left(\frac{183}{Z^{1/3}}\right) + \frac{1}{18}\right]$$

- both density (pressure) and chemical composition (Z) may be spatially dependent

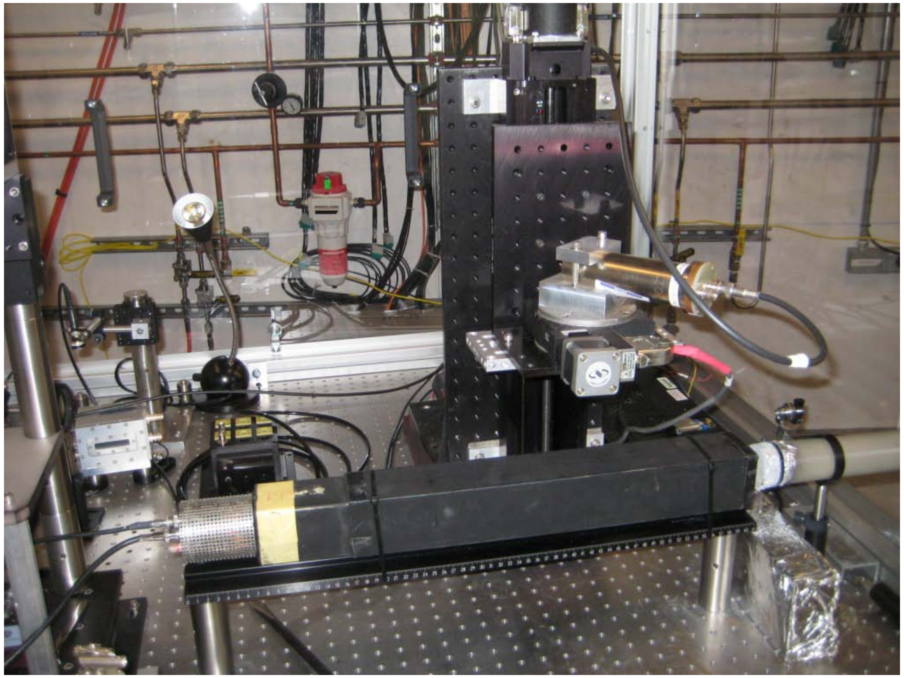
$$P_{GB} = k_B \frac{I}{e} \int_0^{L_{ss}} ds \left.\frac{dT}{dx}\right|_{rad} = k_B \frac{I}{e} T \int_0^{L_{ss}} ds \frac{\rho(s, I)}{X_o(s, I)}$$

Radiation considerations and detection

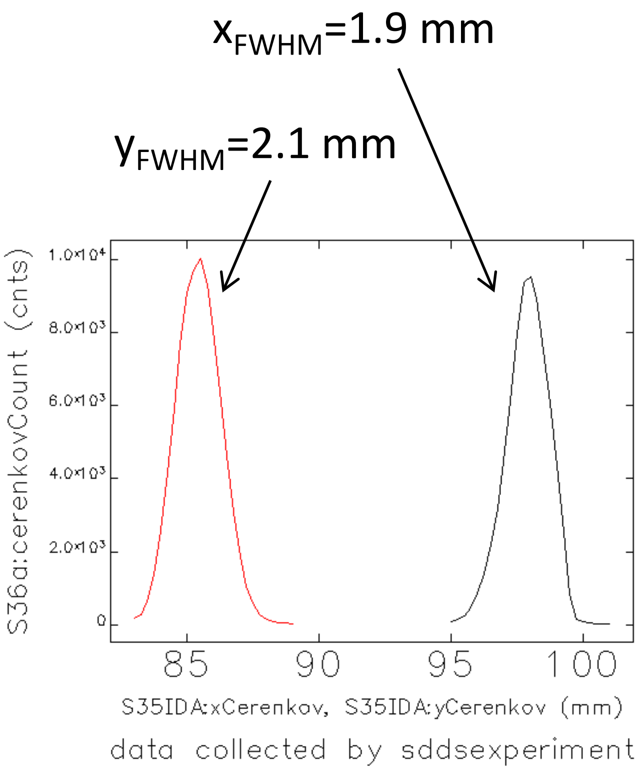
- Due to the dependence of pressure on current, TB-54 suggested that pressure and GB power be measured again.
- The effective Z (chemical composition) actually is the most important factor.
- Fortunately, have been looking at GB in S35 using several different detectors, including an original GB array detector used for LS-260 and 269 work.
- Pb:Glass is 6.35 x 6.35 x 35 cm^3
- Radiation length, X_o=2.6 cm

Radiation detection

Pb:Glass calorimeter detector in S35



Measurements of GB show the transverse size in S35 to be small…



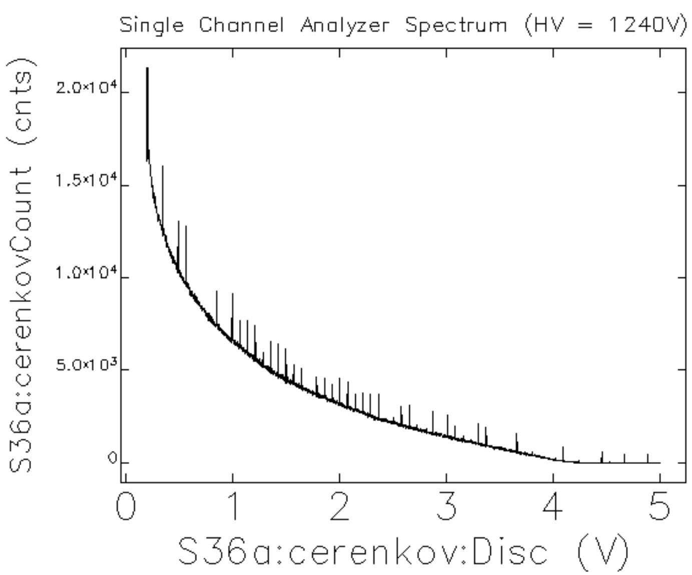
…therefore the transverse size is sufficient to observe virtually the entire shower.

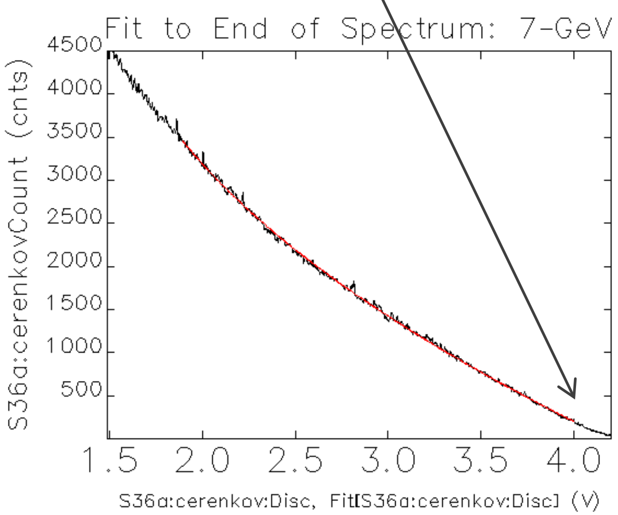
GB measurements: Pulse Height Calibration

- Experiment: Single-channel pulse-height analyzer (SCA) measurement
  - Maximum-energy shower (7 GeV) ➔ Absolute energy calibration
  - Derive height calibration using PMT gain curve.
-

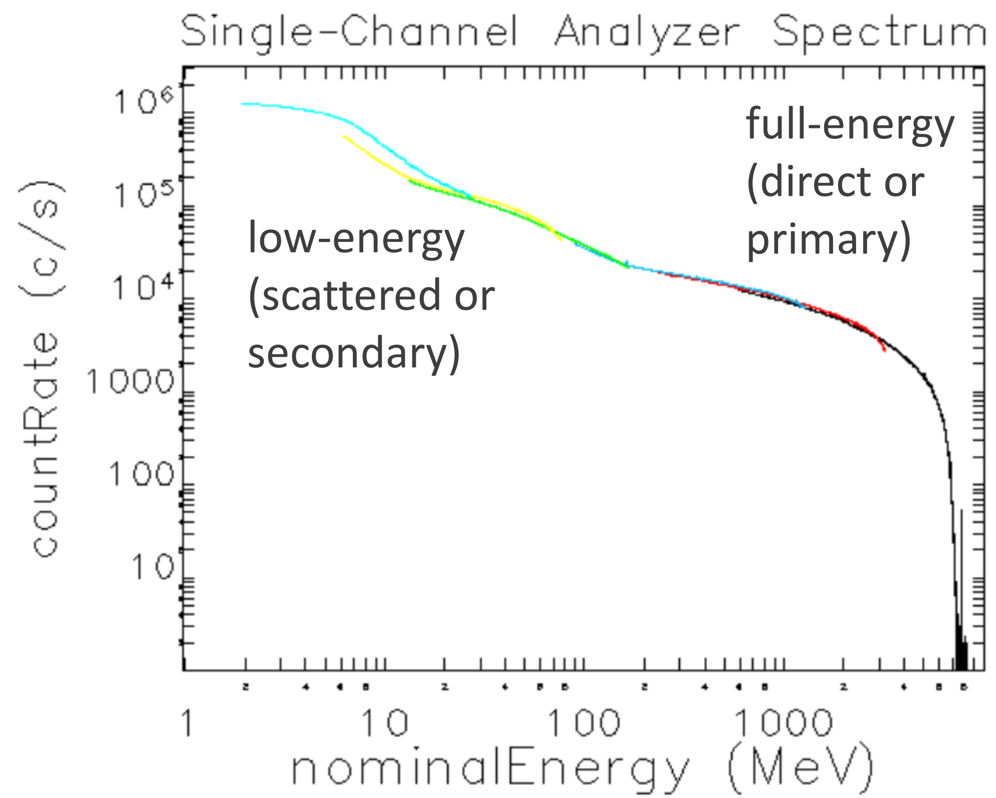
Table 4-1: Calibration coefficient for lead-glass Cherenkov detectors

HV (V)	PMT Current (nA)	Calibration factor (MeV/V)
1950	220	5.50
1800	78.1	15.5
1687	35.9	33.7
1550	12.38	97.7
1448	2.339	259
1350	0.932	649
1240	0.358	**1691**





With the calibration could examine the GB spectrum over 4 orders of magnitude



GB measurements: Extrapolation to 150 mA (24 b.)

- Extrapolation:
  - Pressure is an exponential function of temperature

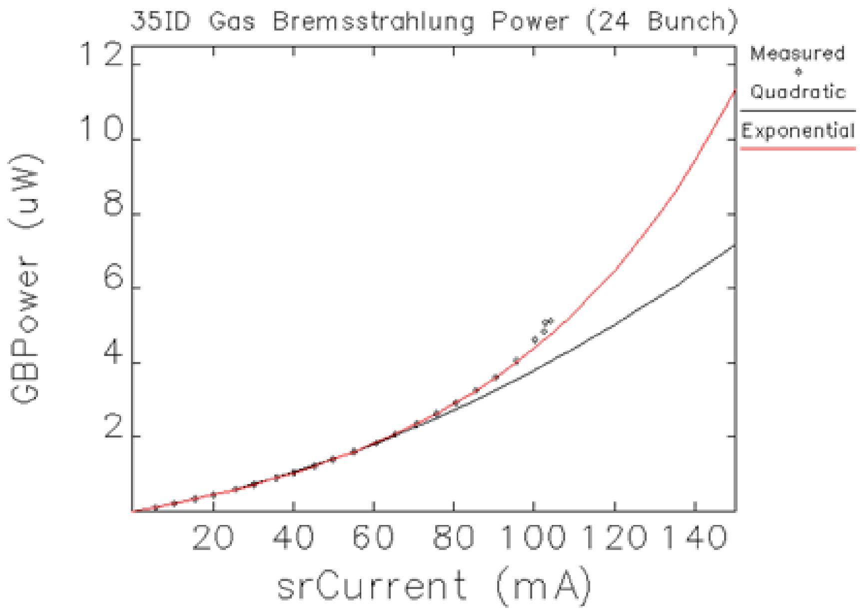
$$R = R_0 e^{-E_R/k_B T} = R_1 e^{-\Delta T/T_1}$$

  - Current ➔ power deposition ➔ temperature rise

$$\Delta T \propto P \propto a_1 I + a_2 I^2$$

Predictions: P_{GB}(150mA)/P_{GB}(100 mA) = 140% (quadratic): 5 μW$\rightarrow$7 μW

P_{GB}(150mA)/P_{GB}(100 mA) = 222% (exponential) 5 μW$\rightarrow$11 μW

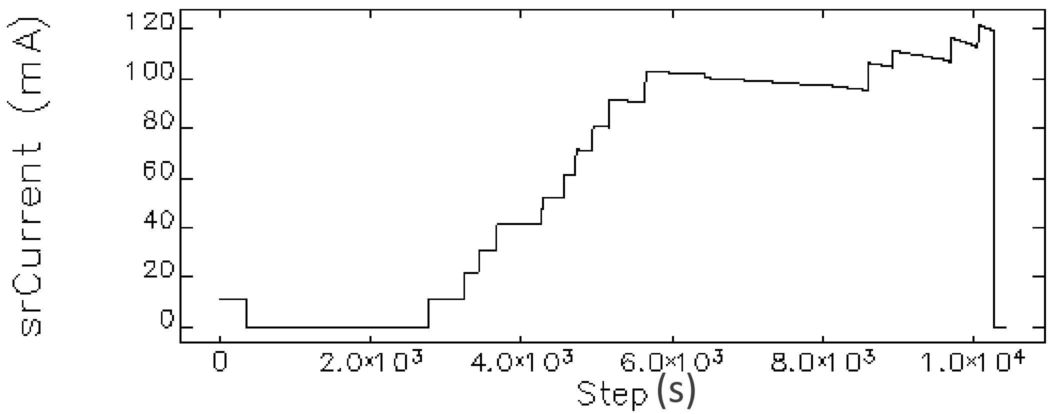


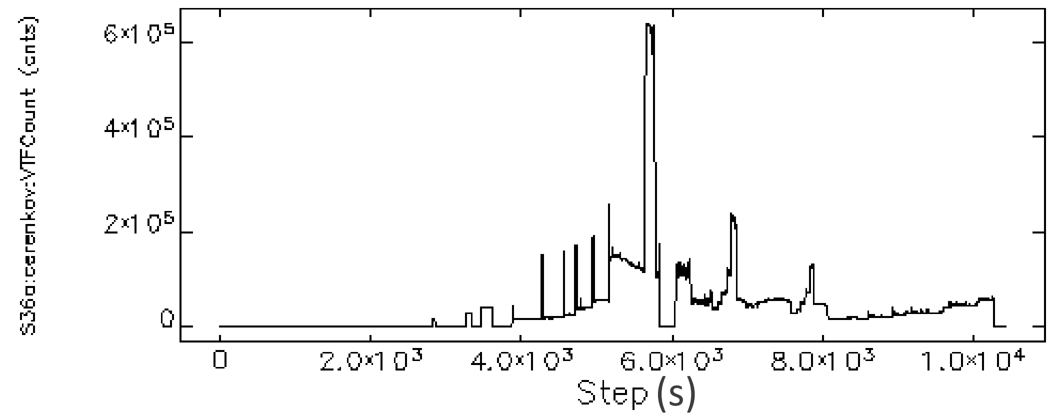
High-Current GB study December 21, 2010

24 bunch fill pattern chosen

Initially, a bit of a struggle.

Early on had beam motion noted. Low chromaticity lattice loaded for P0 feedback studies. Chromaticity had to be measured and adjusted



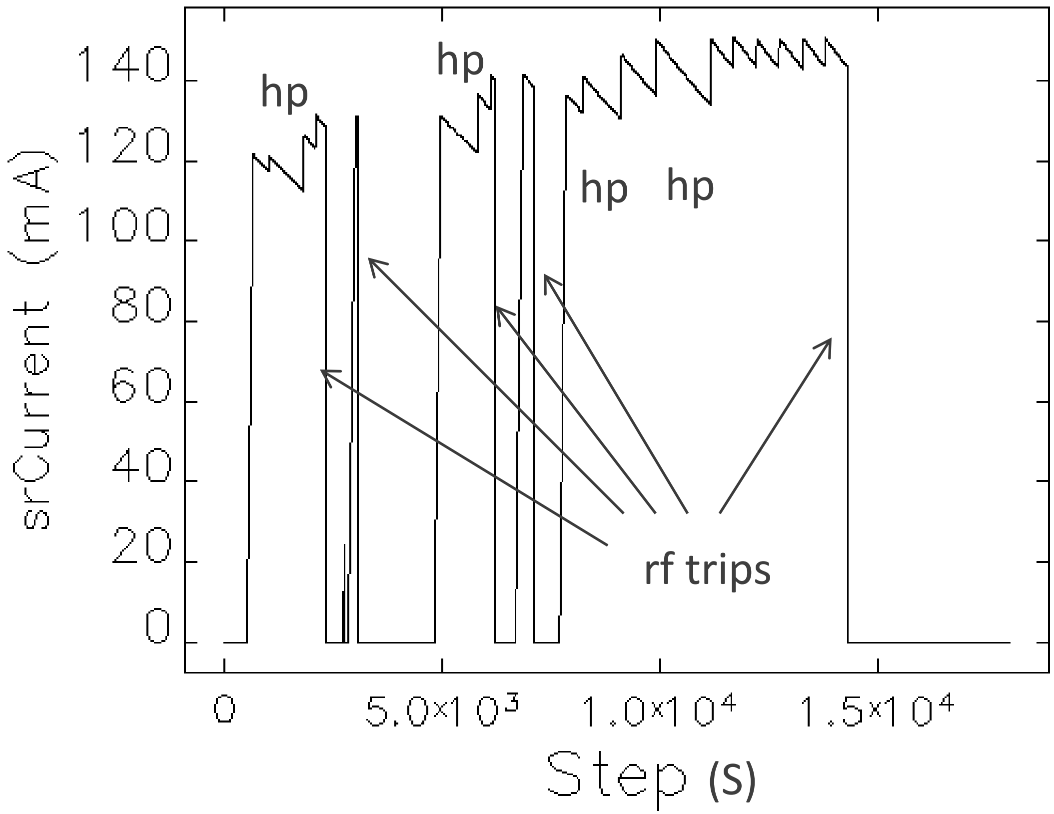


Plots start just after 9 AM and end just before noon

High-Current GB study December 21, 2010

Later, rf trips knocked us out several times.

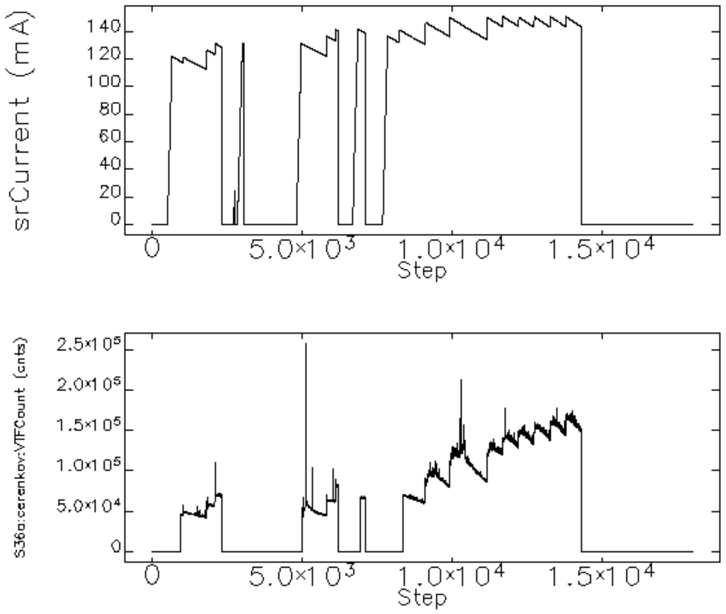
Above 100 mA, increased current in steps of 5 mA; every 10 mA, HP took readings



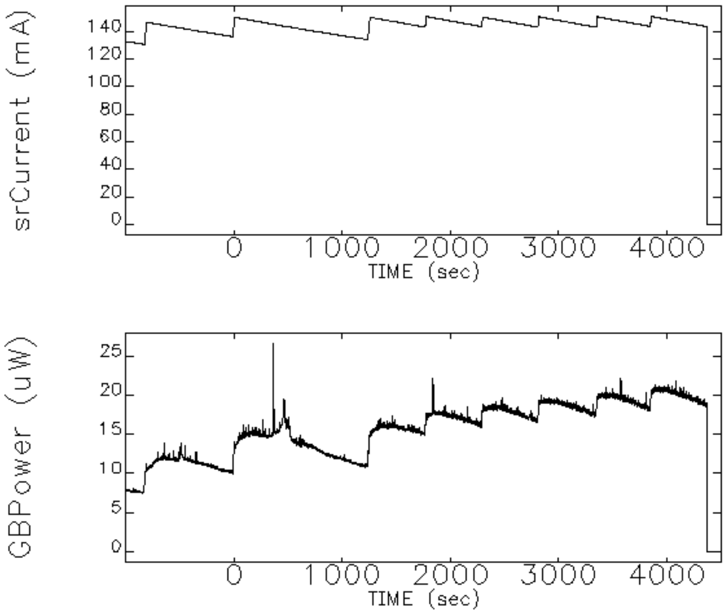
plot starts shortly after noon

High-Current GB study December 21, 2010

SR current, GB counts 2nd half

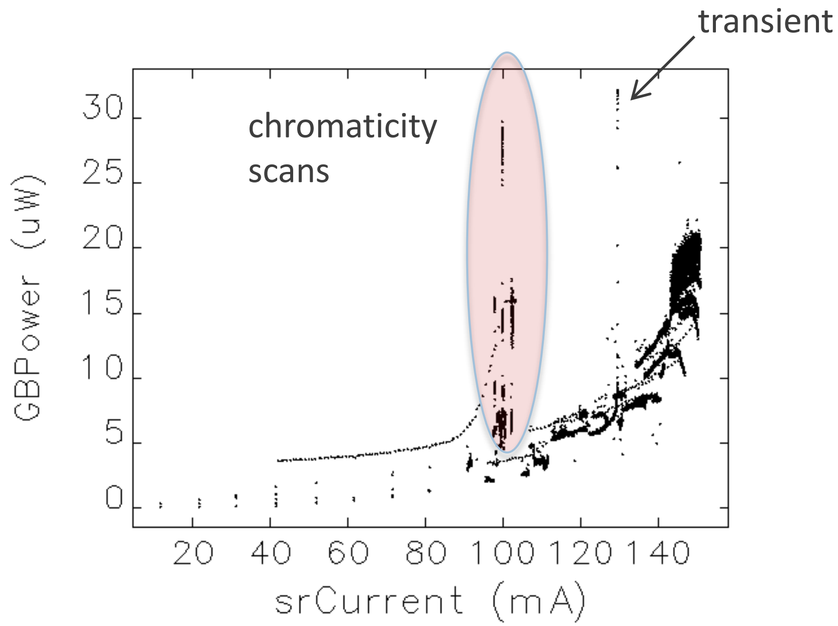


Last 90 minutes of the study:

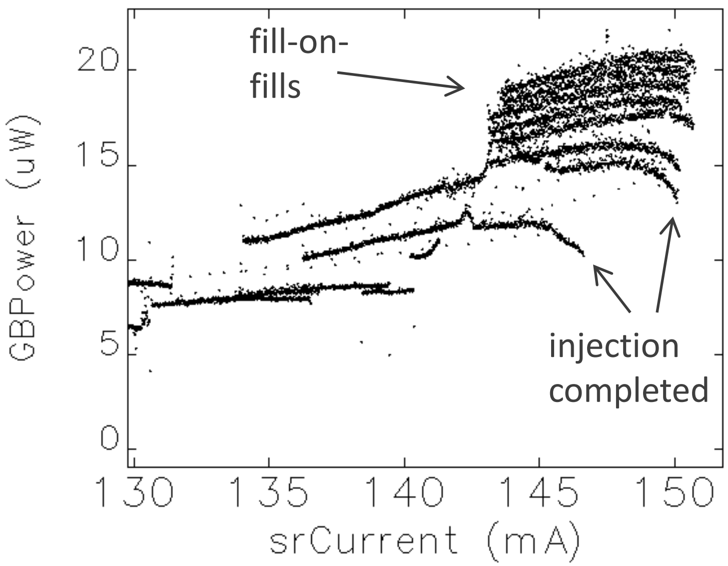


GB power vs. current

Over the entire study



zooming in on I>130 mA



SR Arc—pump locations (from LS-260)

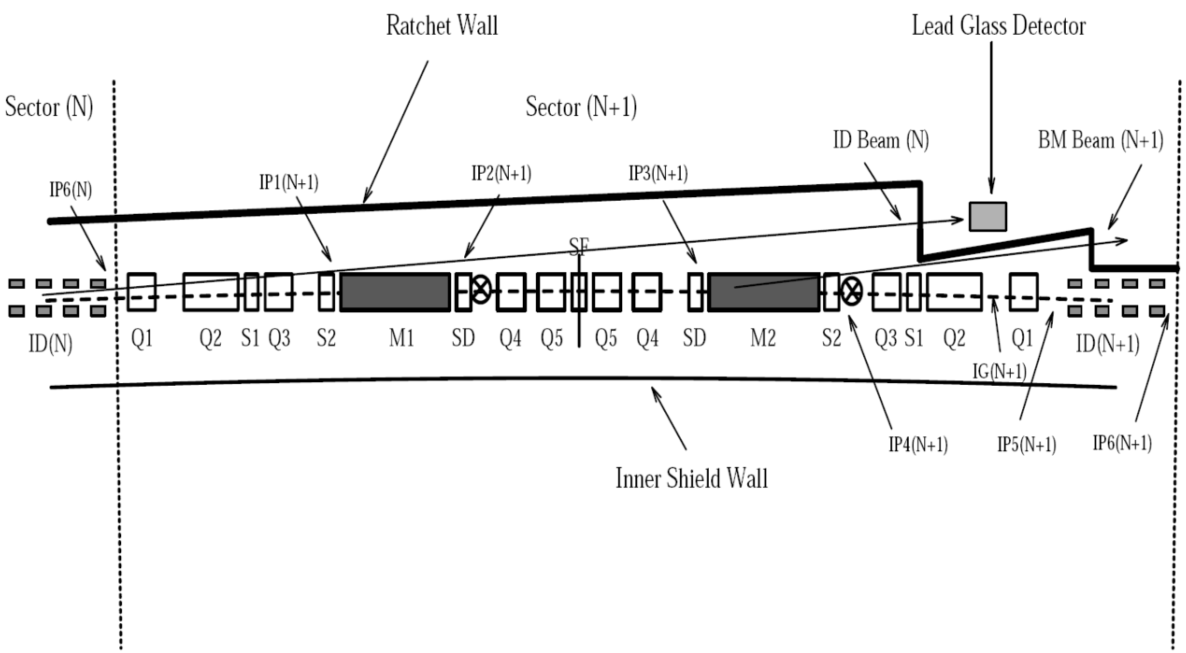
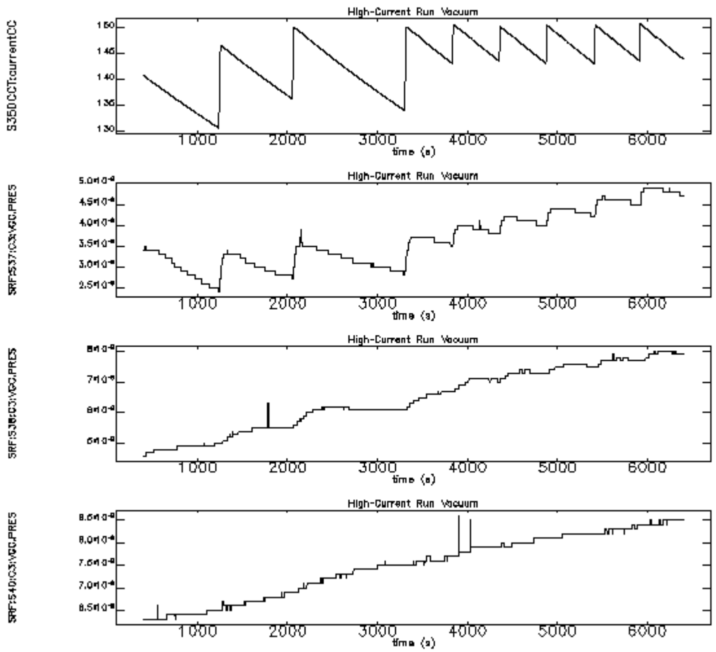


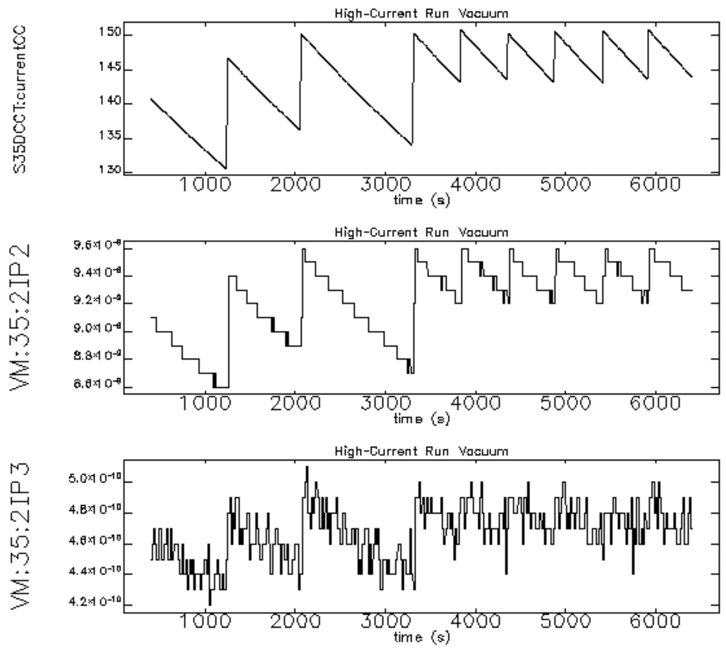
Figure 10: Layout of a sector ID(N) of the APS storage ring. The photon beamline from ID(N) traverses also through the sector ID(N+1). Locations of various ion pumps (IP) and ion gauges (IG) that are in sector N and N+1 are shown. The photon beamline of ID(N) separates from the storage ring after the IP2 pump location of sector (N+1). The figure is not to scale.

Pressure in other regions during the study

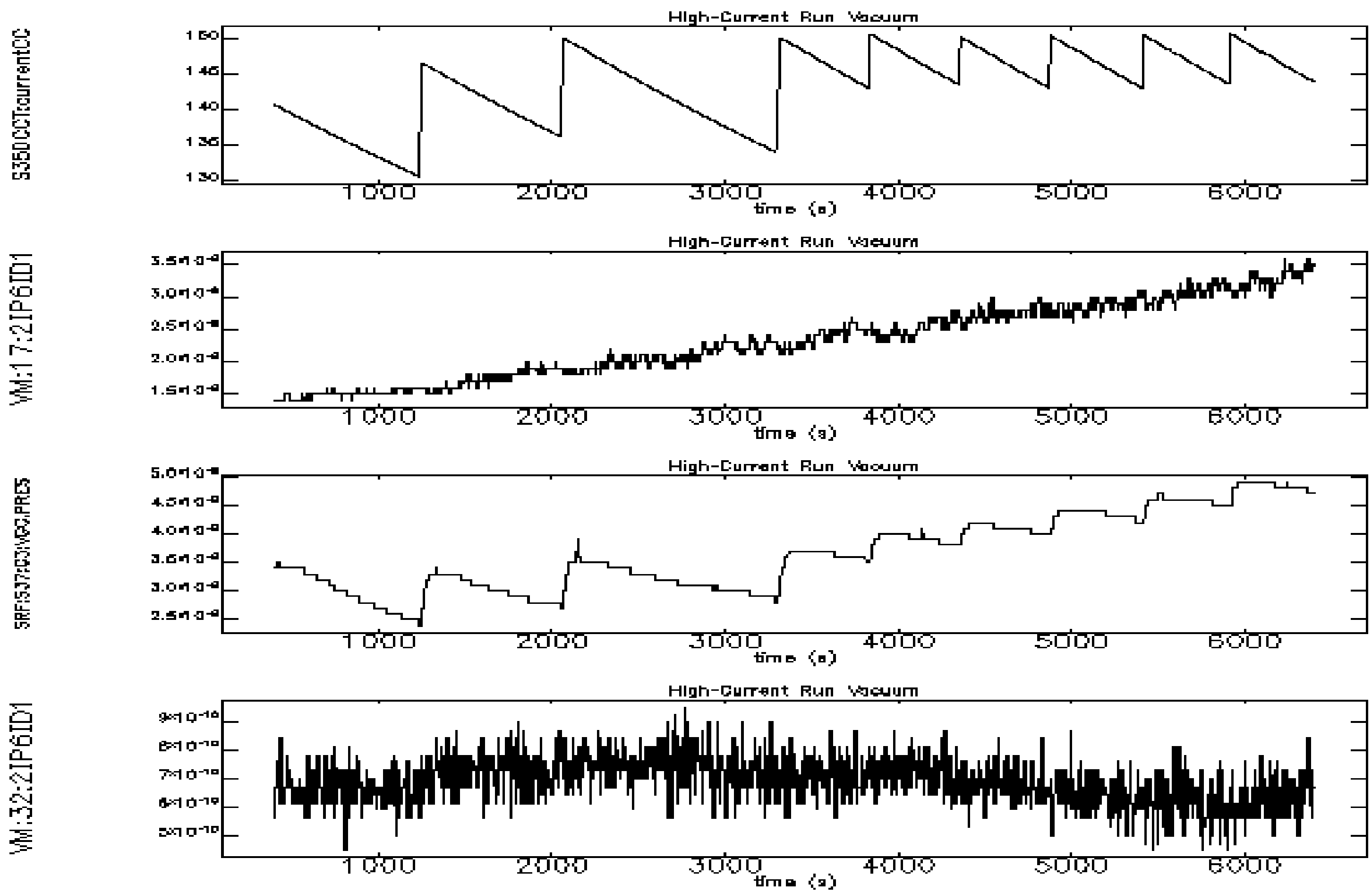
RF cavities



S35 in short straight between dipoles



Pressure in other regions during the study



High Current results/limitations

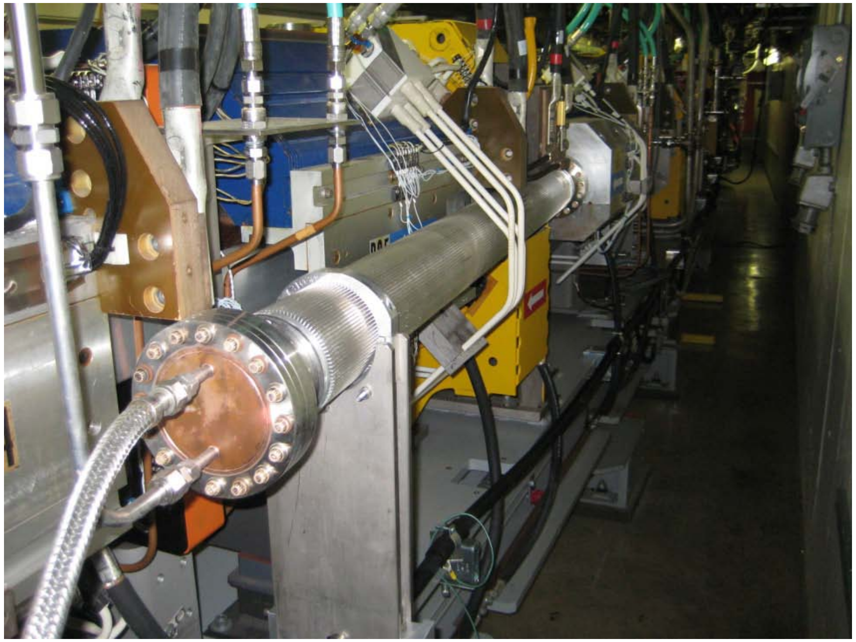
- Did obtain GB data for 24 bunch fill pattern up to 150 mA
- Shutters were open, HP observed reasonably low rad levels within limits
- We did not have an RGA
- Did not have pressure data in the 35-ID straight section; tests inconclusive
- Did observe pressure rises in other areas that are similar to GB power measured
- Learned after the test that both ion pumps in the sector were not operating
- Need to repeat the test with working pumps (ion pump current provides pressure readings)
- Exceeded GB power prediction by roughly a factor of two
- Need to understand mechanism—heating, multipactoring, or something else

Gas bremsstrahlung—ID vacuum chamber diagnostic

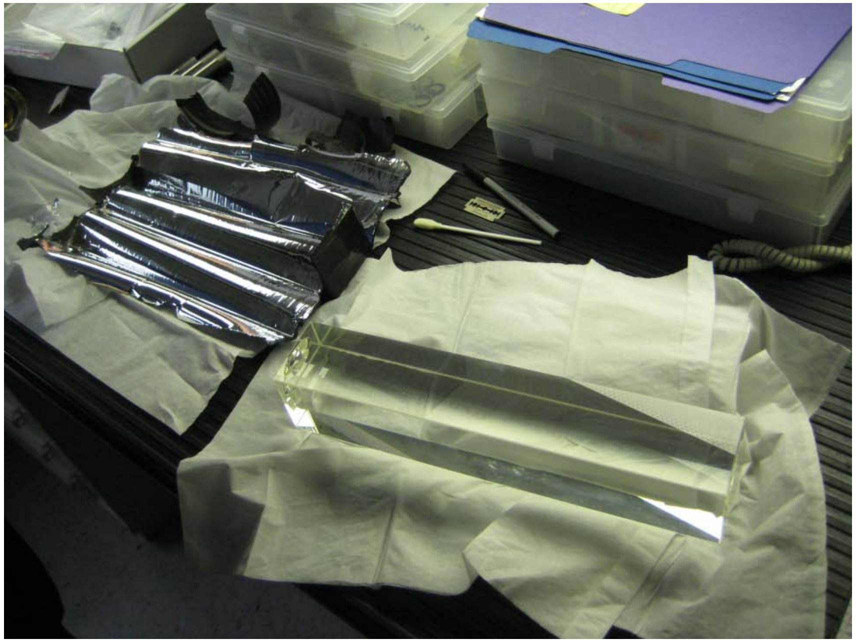
- Provides a quasi-local view of target density within an ID vacuum chamber (integrated along the line of sight)
- Response can be very fast
- Need RGA for chemical composition
- Need to better understand beam/gas dynamics especially at higher current
- Draft Proposal for diagnostic has been written

Plans for a permanent GB diagnostic

Initially install in S28 and S36; the diagnostic in S36 can remain



Just found: Pb:Glass calorimeters!
—they need some work but radiators should be useable



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Thank you