High-Power Beam Transmission Test

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Motivation: DarkLight experiment

- Search for Dark Matter production in e-p collisions:
  "Needle-in-a-haystack" problem

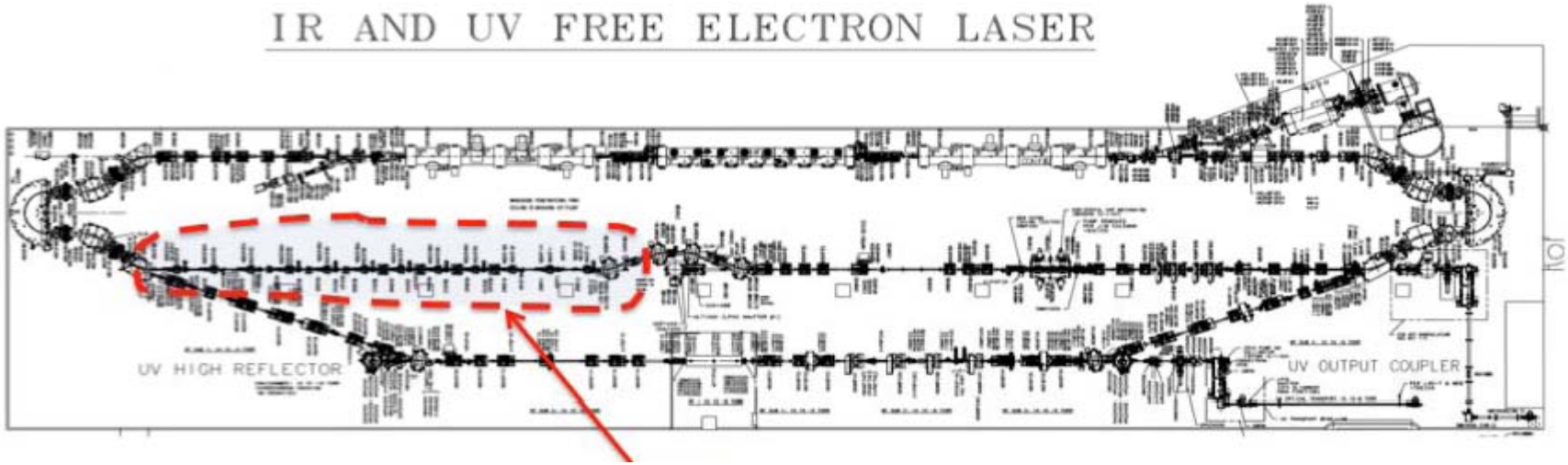
- Detect all reaction products including recoil protons
  → gas target with internal proton detectors

- Maximal luminosity
  → max. target density (10^{19} atoms/cm^2)
  → max. beam current (10 mA, 1 MW)

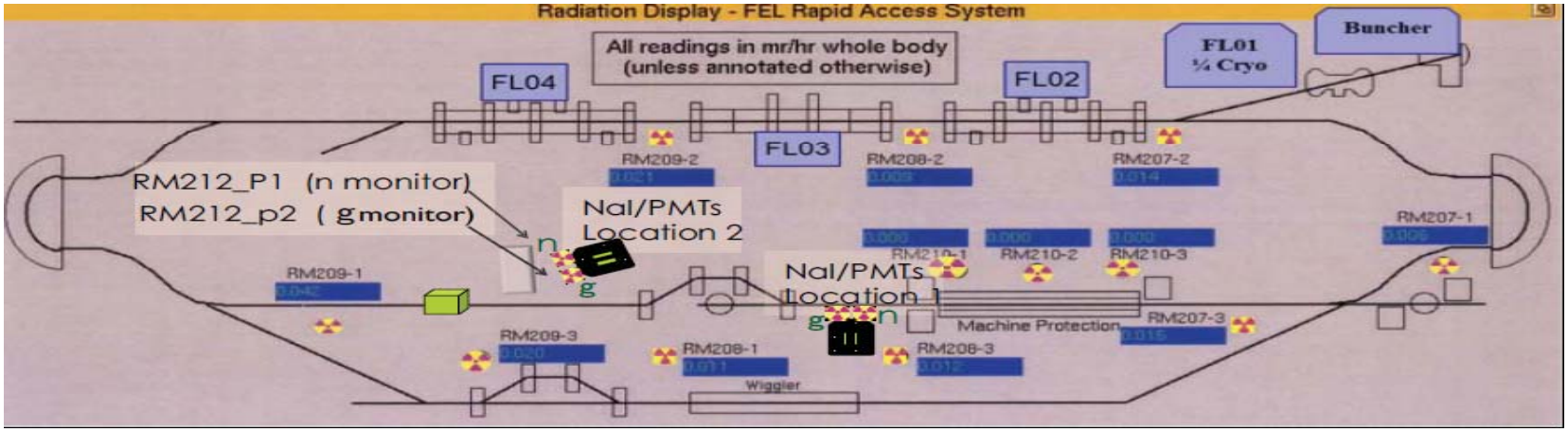
- Windowless high-density gas target
  → small beam entrance & exit apertures (~2mm) to reduce pump sizes
  → minimal beam losses (ppm) for minimal background

Beam Transmission Test Site
J-Lab's FEL Beam (100-MeV electrons, 5 mA)

Test Area

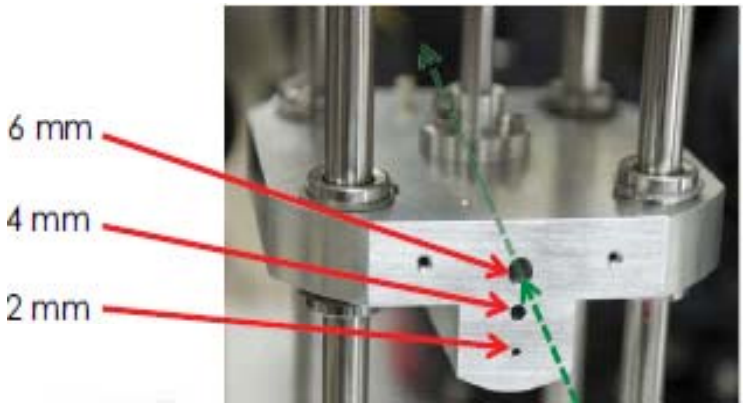


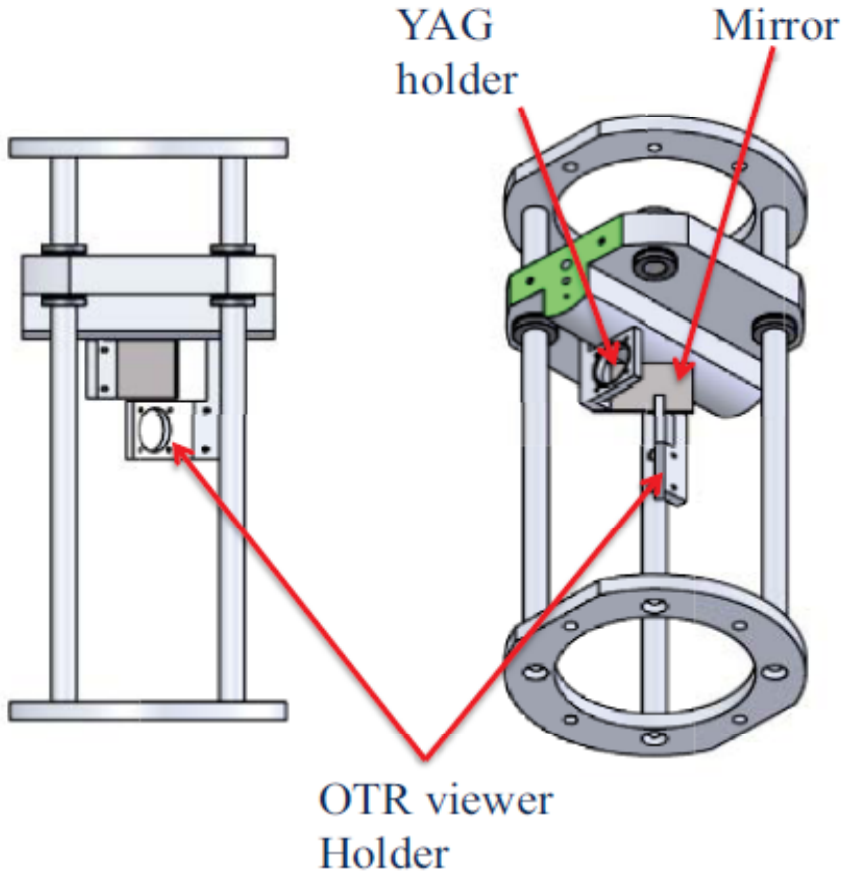
Loss monitors



Aperture Block

- Aluminum Block (AB) remotely inserted in beam pipe: 2-, 4-, 6-mm diameter aperture s, 127 mm long
- 2 beam and halo profile monitors (YAG crystal, OTR)
- RTD temperature sensor in AB.



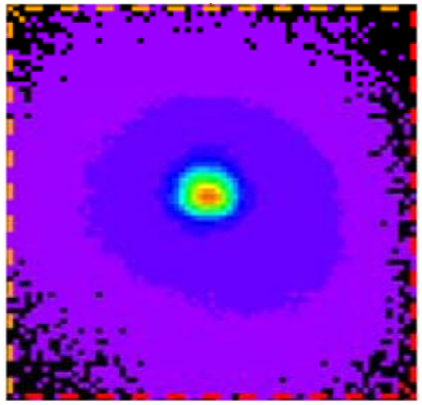


Beam Setup

- Beam requirements
  - Maximal beam current
  - Small momentum spread
  - R.m.s. beam radius much smaller than 1 mm
  - Minimal beam halo outside 1-mm radius
- Machine tune
  - Cross-phasing linac for minimal $\Delta p/p \sim 2‰$:
    bunch accelerated on rising RF wave in module 1 & 3
    bunch accelerated on falling RF wave in module 2
  - Optimized RF voltage distribution between modules to minimize halo from field emission
- Test region focusing
  - Quadrupole triplets up- & down-stream of aperture
  - Mini-beta ($\beta \approx 0.2$ m) region at aperture
  - Additional quadrupoles for phase advance and halo control
- Halo management
  - Moderate bunch charge of 60 pC for minimal halo at source
  - Small $\Delta p/p$ to minimize momentum tails, dispersion errors, chromaticity effects from mini-beta region
  - Cross-phasing to allow long bunches for minimal wake field effects in apertures

Beam Tune

- Low-power beam: Full bunch charge and length, low rep. rate
  - Set up cross phasing, lattice dispersion, and betatron tune
  - Center orbit through 6-mm and 2-mm apertures
  - Minimize beam spot size at aperture position (OTR, YAG)
  - Retune return beam for minimal loss and beam-break-up (BBU)
  - Minimized halo size (YAG) , test several bunch charge and rep. rate combinations
- Raising beam power (rep. rate) with fixed 60-pC bunch charge
  - Minimized halo losses through 2-mm aper.
    temperature rise of ap. block; neutron and photon background
  - Increase rep. rate in steps, fine-tune for minimal halo loss after each step
  - Final beam power ≈ 450 kW (4.5 mA, 75 MHz, 60 pC, c.w.)



Area = 1 mm x 1 mm;
Best Gaussian fit: σ_x = 50 µm, σ_y = 52 µm

Transmission Runs

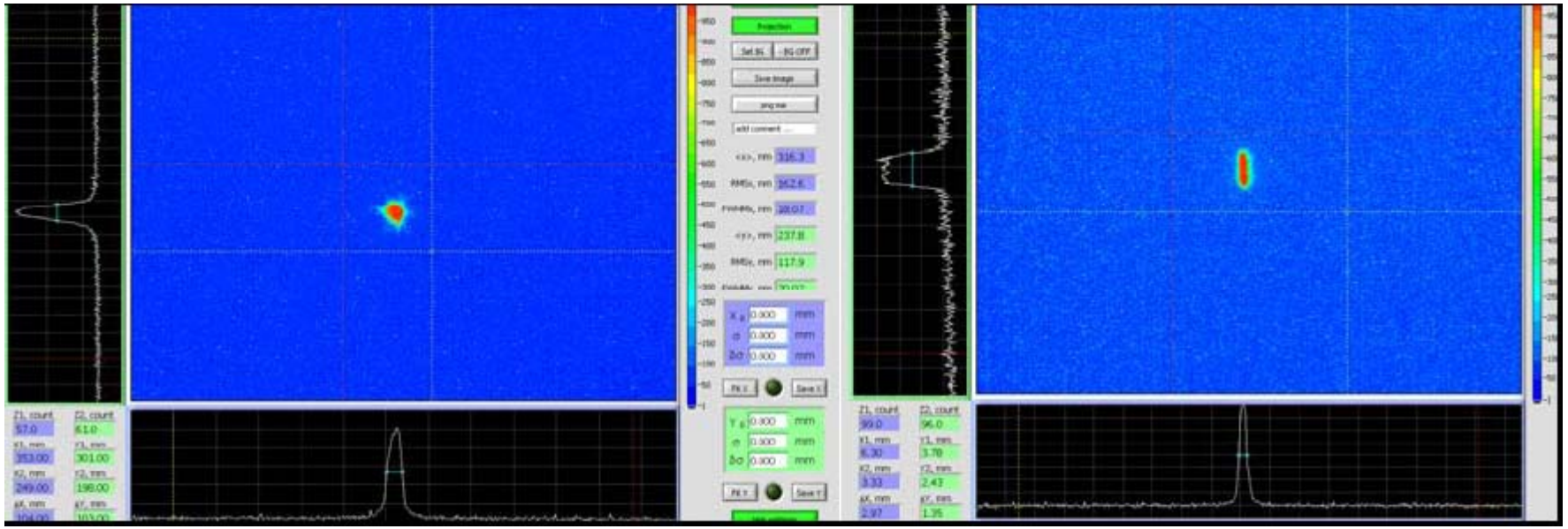
- Lattice fine-tuning for minimal losses at ion chambers and PMT's
- Fine-tuning (steering & focusing) at aperture region for minimal background
- BBU caused by small energy drifts:

  Small Δp/p inhibited Landau damping,

  Energy drifts coupled to chromaticity shifting vertical phase advance leading to BBU

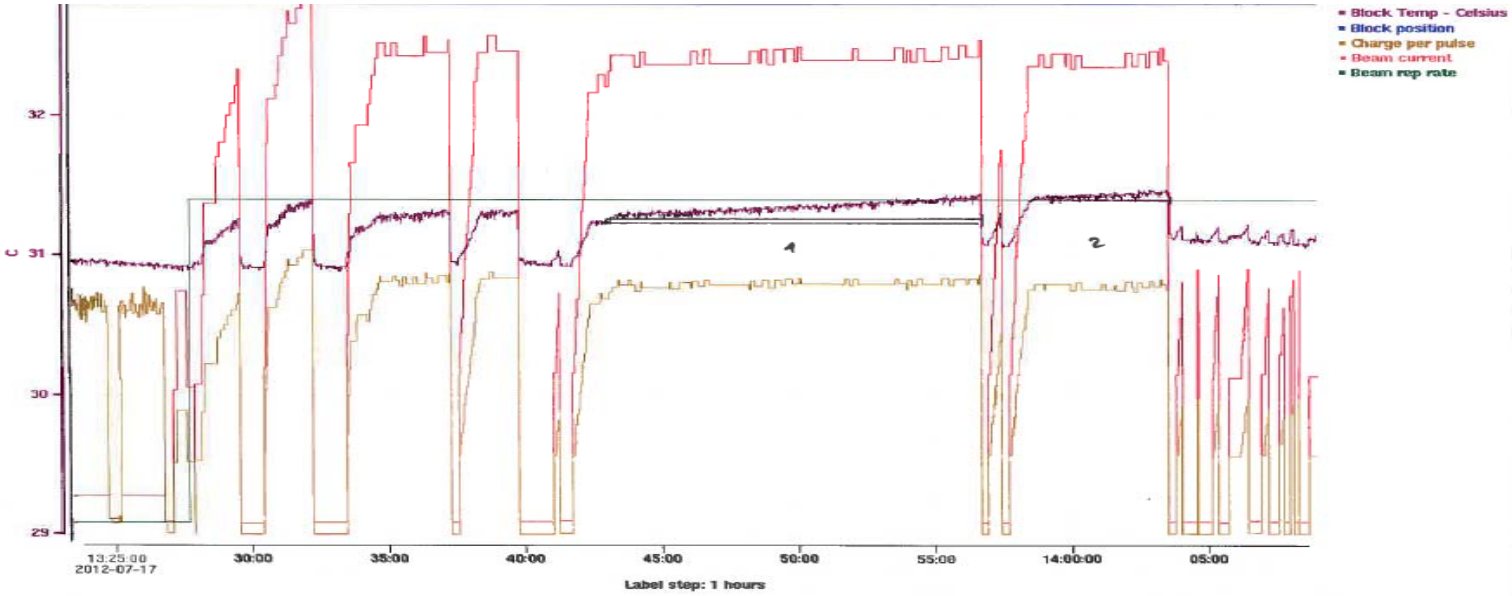
  → Maintain stability by monitoring and minimizing vertical beam size
- Final 8-hour transmission run through 2-mm aperture:

  Instabilities controlled by stabilizing energy at injection and recirculator

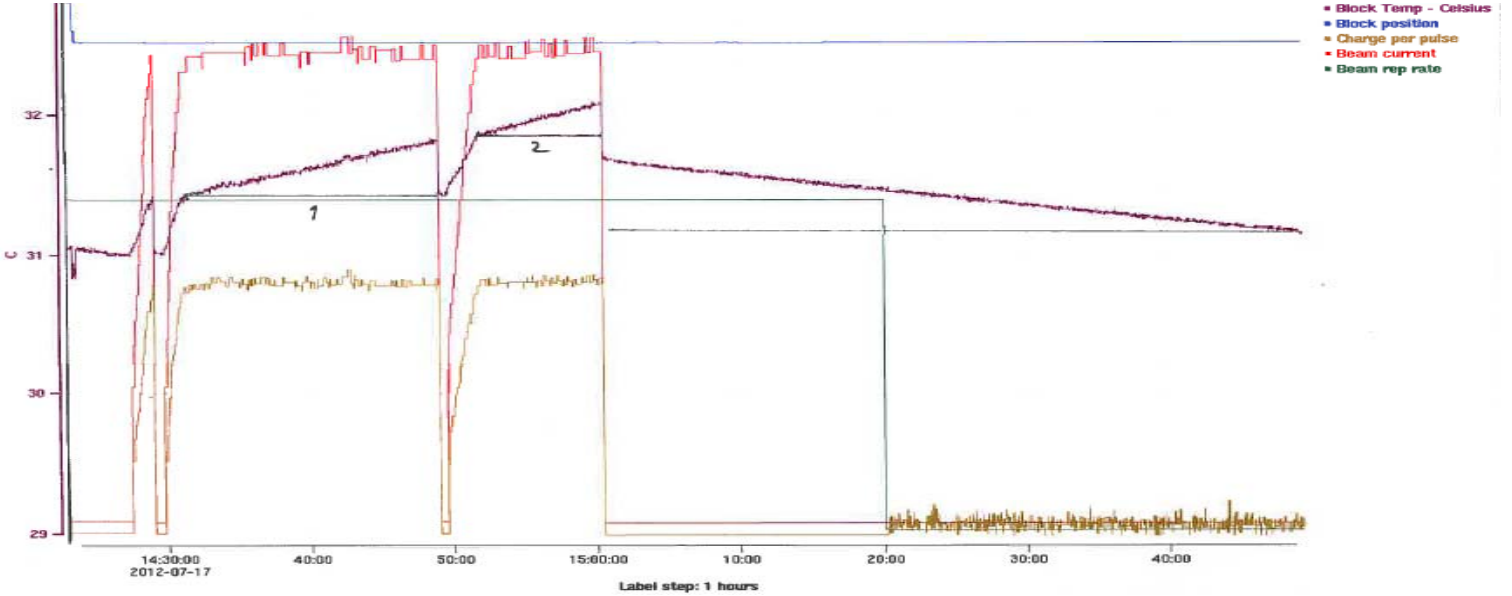


Test Results

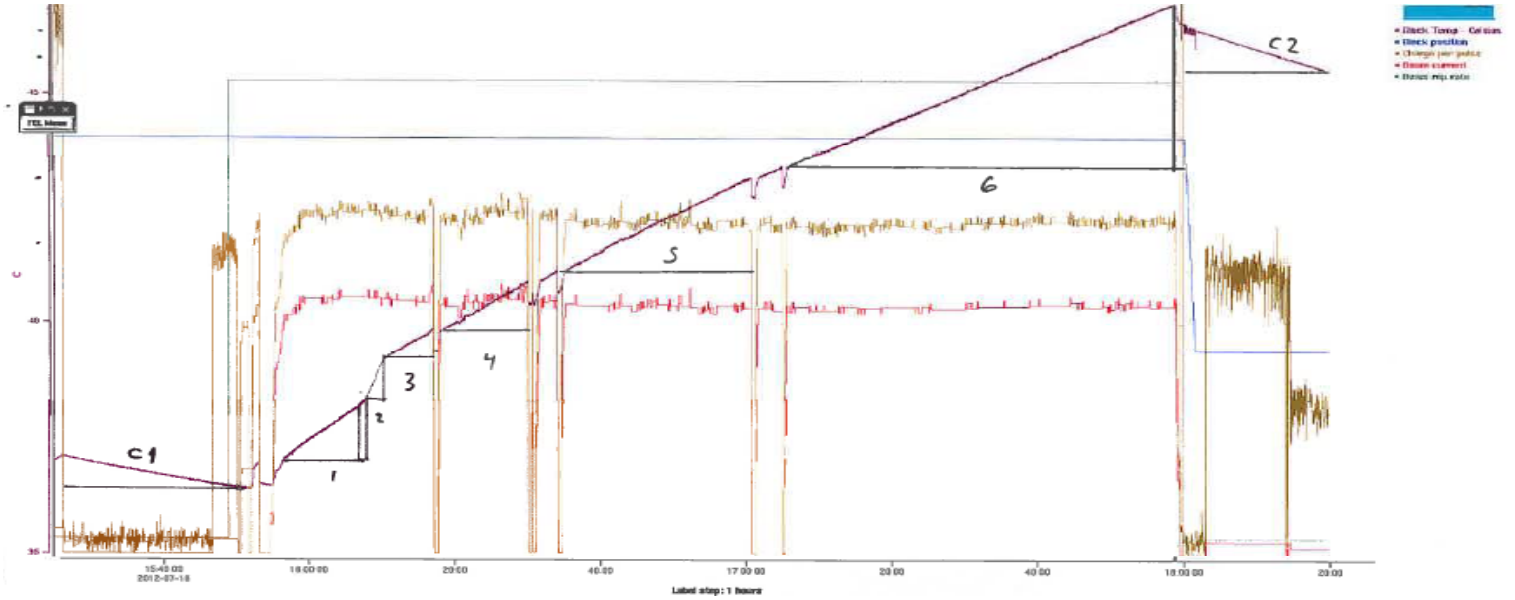
Run 1:
6-mm
aperture;
22 min.



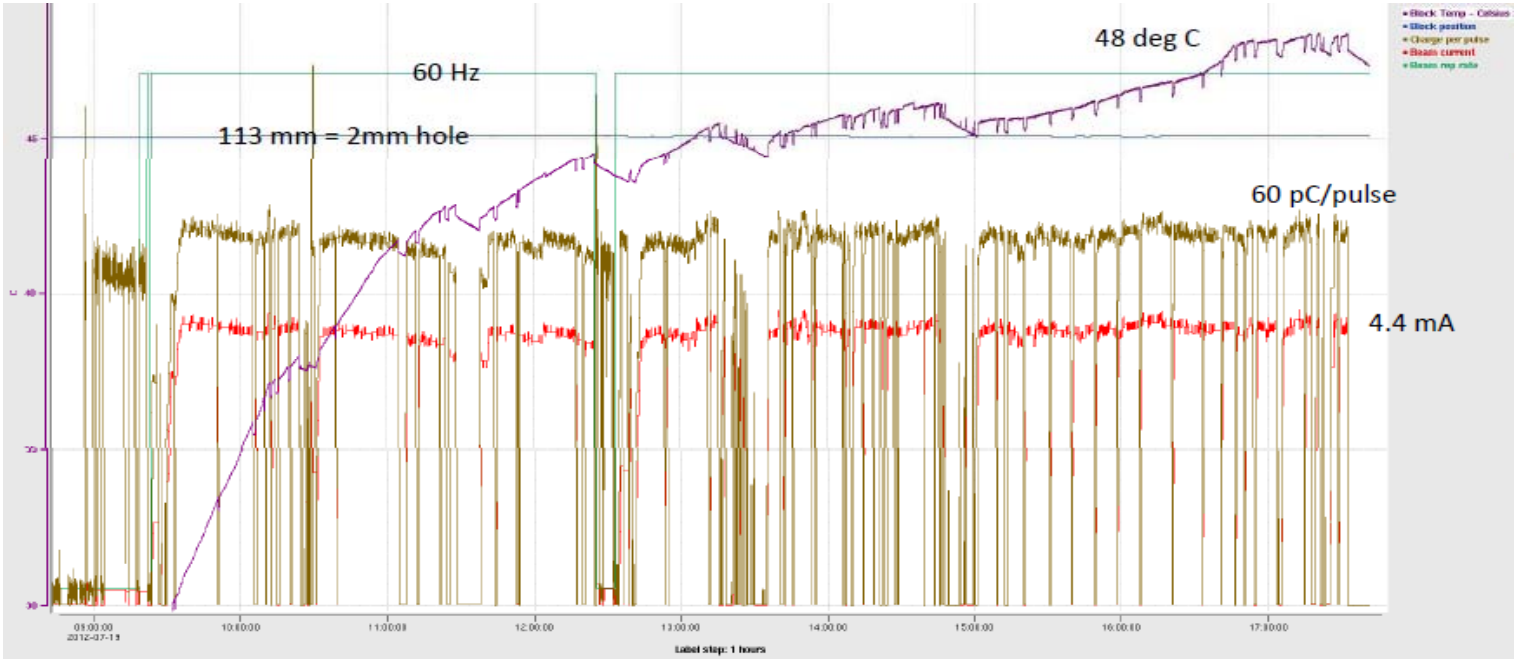
Run 2:
4-mm
aperture;
30 min.



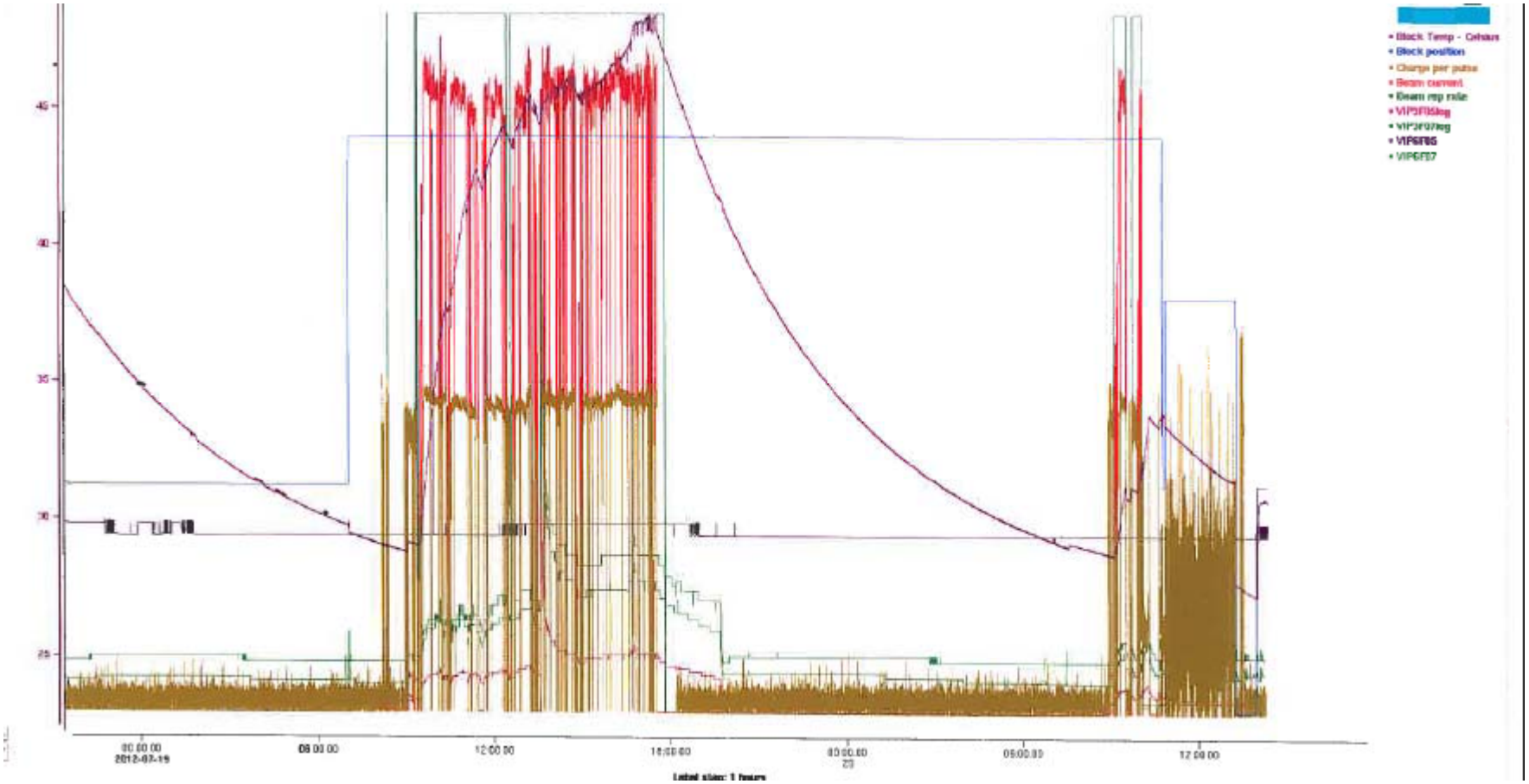
Run 3:
2-mm
aperture;
124 min.
(2h)



Run 4:
2-mm
aperture;
478 min.
(8h)



Cooling runs



Beam power deposition in the AB

$$P_{block} = c_p m \left(dT / dt\right)_{block} + P_{cool}$$

Cooling by conduction and radiation to the beam pipe

$$P_{cool} = \left(T - T_0\right) c_p m / \tau = 0.043 \left(W / {}^{o}C\right) \cdot \left(T - T_0\right)$$

where $c_p m = 920\ J / {}^{o}C$; $T_0 = 27.2\ {}^{o}C$; $\tau = 6\ \mathrm{h}$

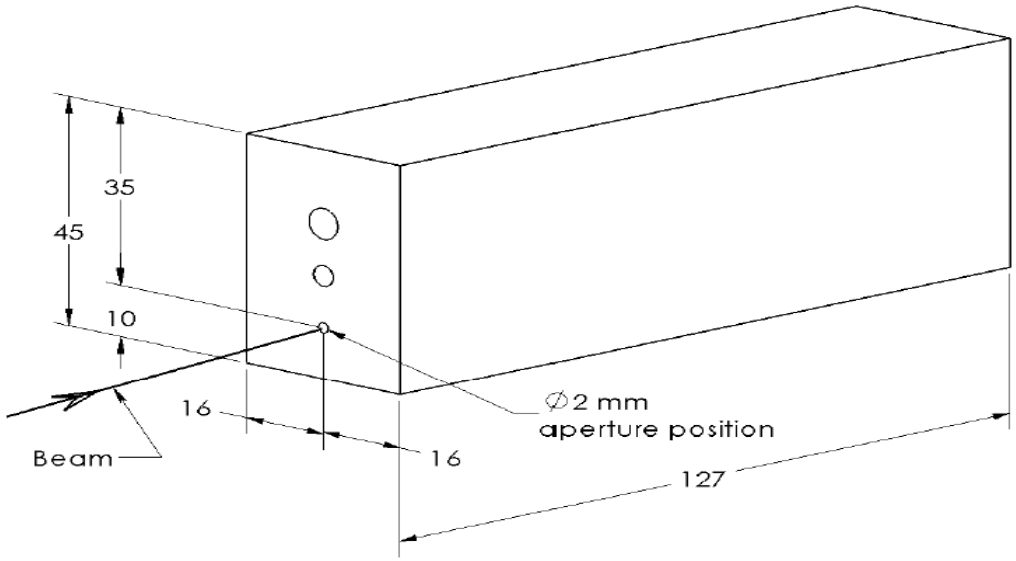
Measure integral energy deposited in the AB over time Δt:

$$E_{block} = \int_{t_1}^{t_2} dt \cdot P_{block} = c_p m \left[\Delta T + \left(T_{ave} - T_0\right) \Delta t / \tau\right] \equiv \Delta t \cdot P_{AB}$$

where $\Delta T \equiv T(t_2) - T(t_1)$; $\Delta t \equiv t_2 - t_1$

Run	apert.	$\Delta t(min)$	$\Delta T(^oC)$	$T_{ave}(^oC)$	$P_{AB}(W)$	$I_{ave}(mA)$
1	6 mm	22	0.21	33.7	0.42	3.50
2	4 mm	30	0.64	31.7	0.52	3.72
3	2 mm	124	10.5	42.6	1.95	4.25
4	2 mm	478	19.1	43.5	1.31	4.22

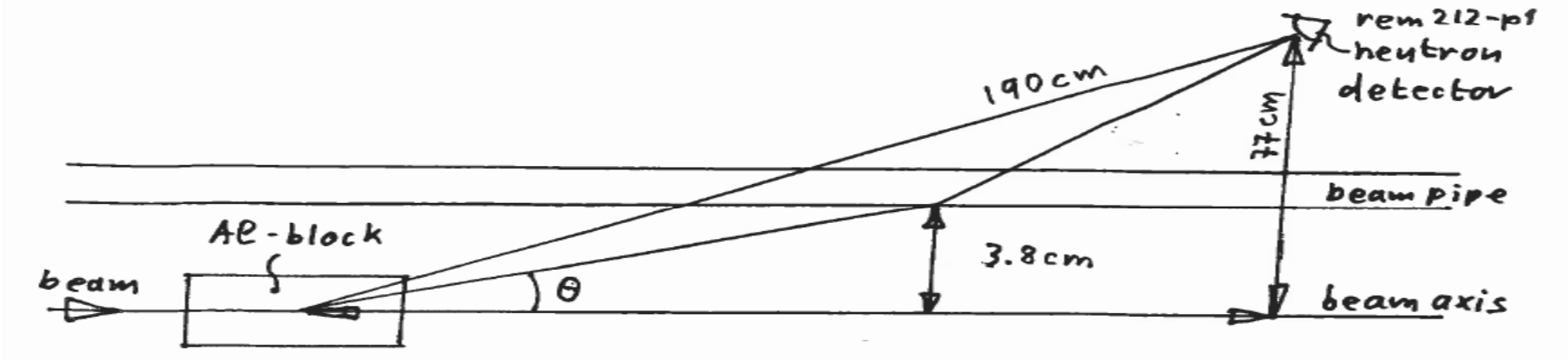
Beam power loss mechanism



- Beam halo electrons intercepted by the AB
  - Electromagnetic shower & secondaries; ionisation energy loss
  - FLUKA modeling indicates 50% of intercepted halo power deposited in AB
- Beam energy loss by wake field interaction with AB
  - Function of beam pulse structure and aperture geometry
  - Halo-independent

Neutron production

- Neutron from Giant-Resonance interaction of e.m. shower generated by intercepted halo electrons



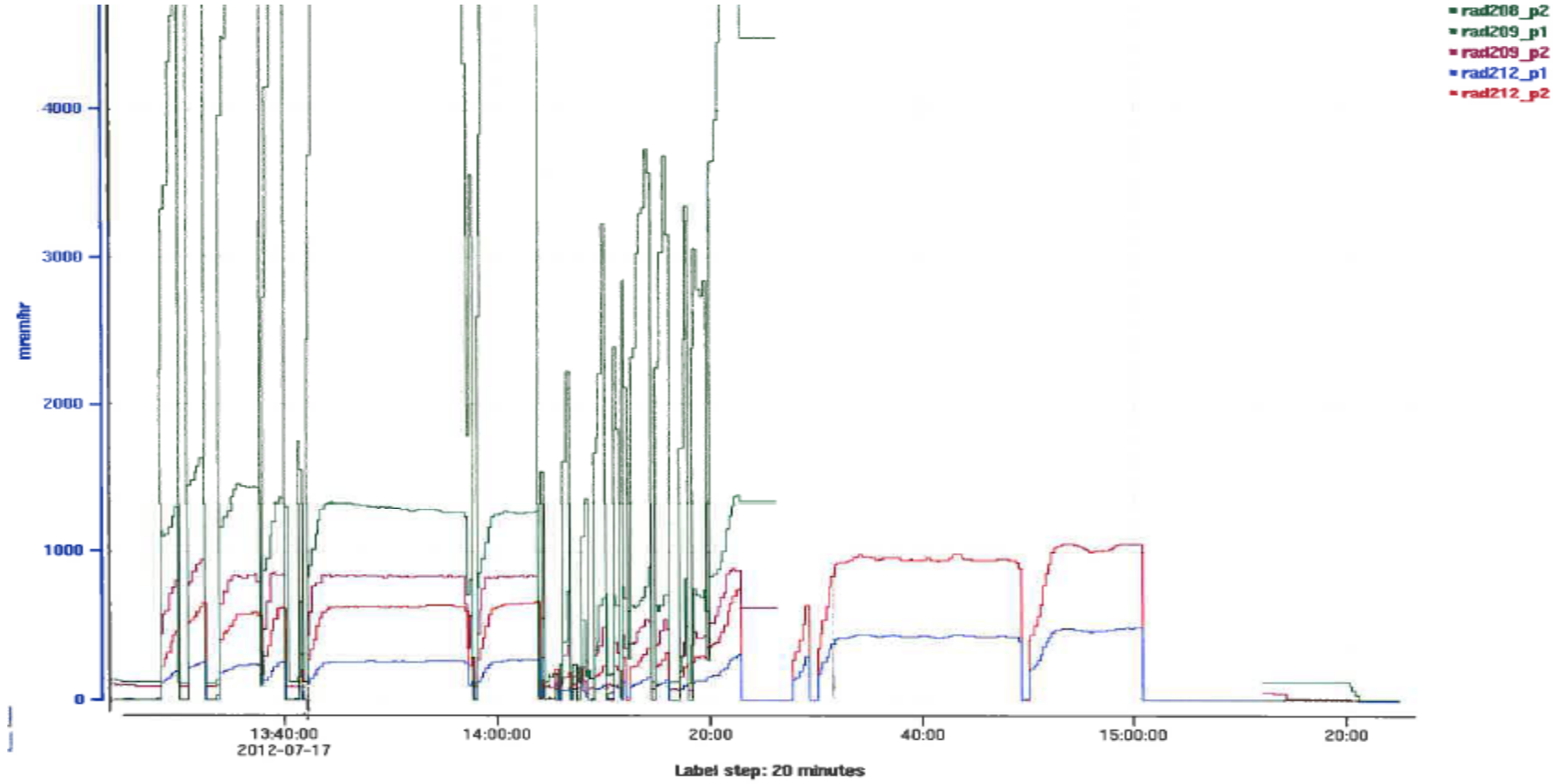
  - n-production in AB
  - n-production by escaping shower in beam pipe
- MCNP modeling shows expected n-flux density at rad212-p1:

$$\frac{dN_n}{dA\,dt} = 3400\ \frac{n}{cm^2 s}$$ per Watt of intercepted halo power

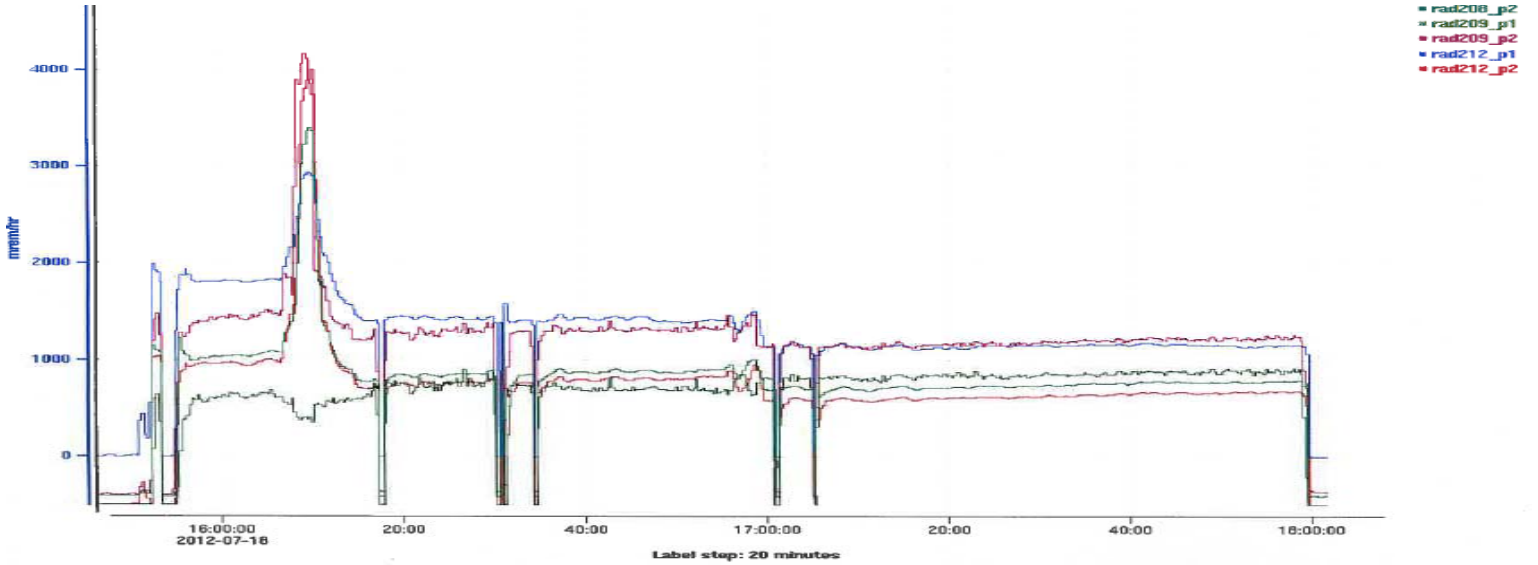
(~3 x flux density expected for a very thick AB)

Measure neutron fluxes from rad212-p1 (Canberra NP100B rem counter)

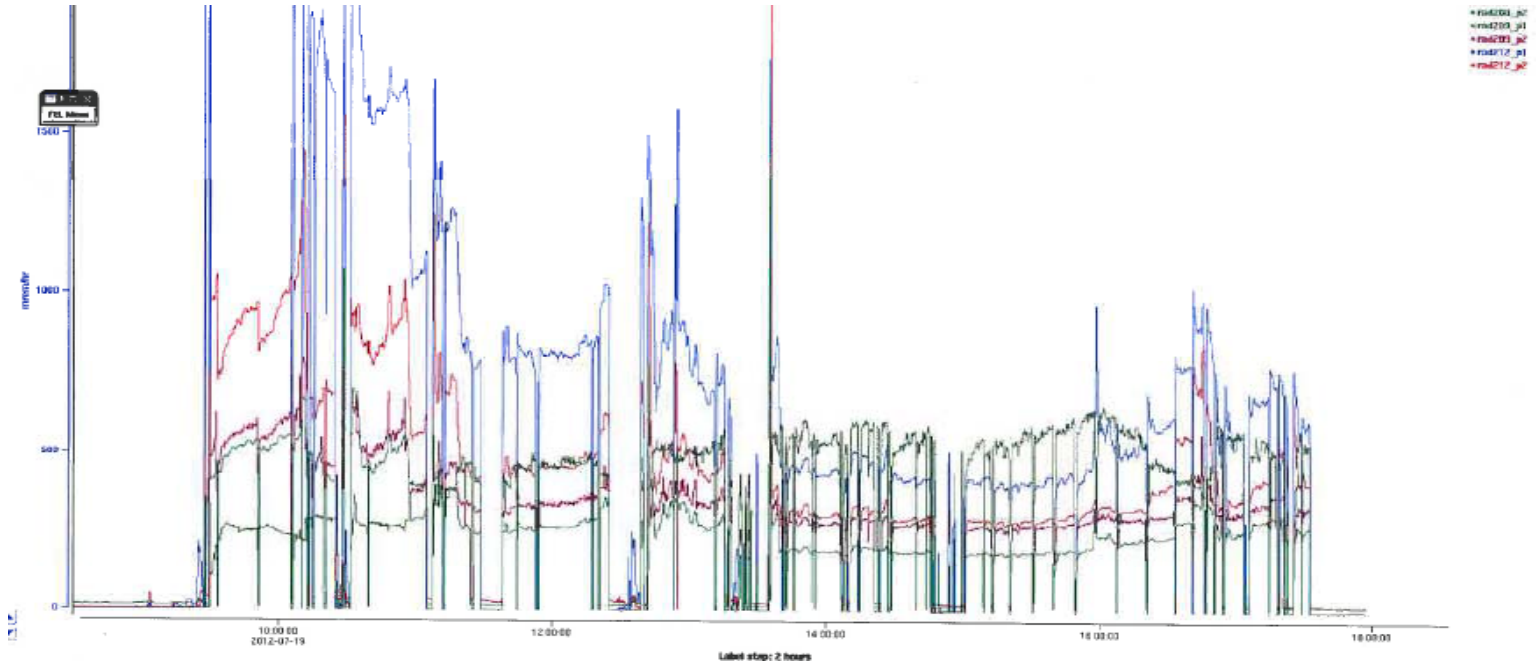
Runs 1 & 2 (6-mm & 4-mm apertures)



Run 3:
2-mm
aperture

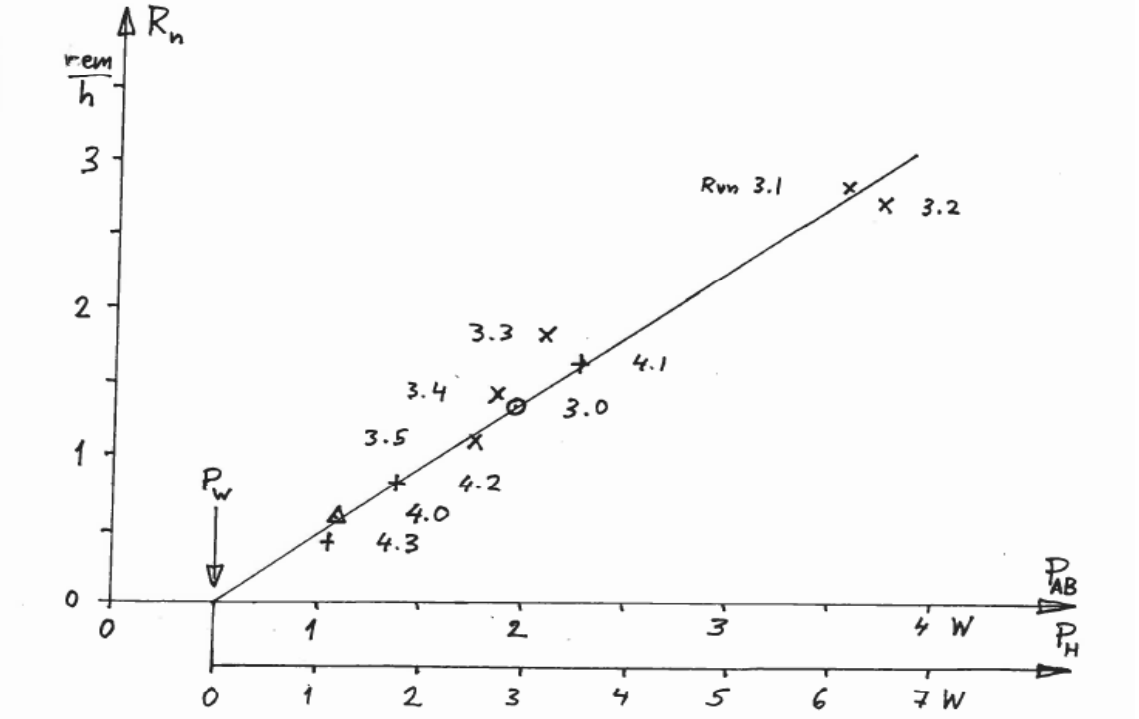


Run 4:
2-mm
aperture



Compared measured neutron dose rates R_n with AB power P_{AB} for several stable beam periods in runs 1 – 4.

Plot of R_n vs. P_{AB} for runs 3 and 4 (2-mm aperture)



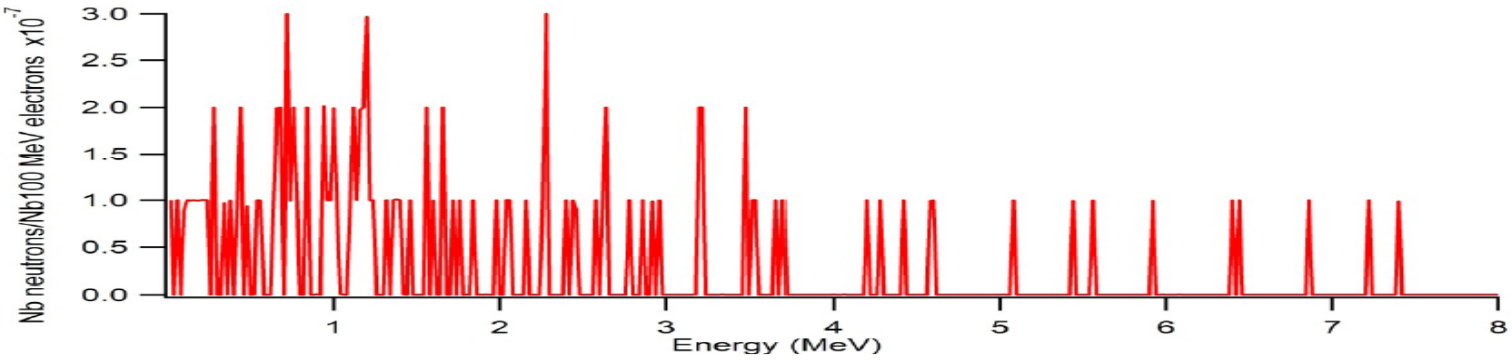
Straight-line intercept = wake field power P_W

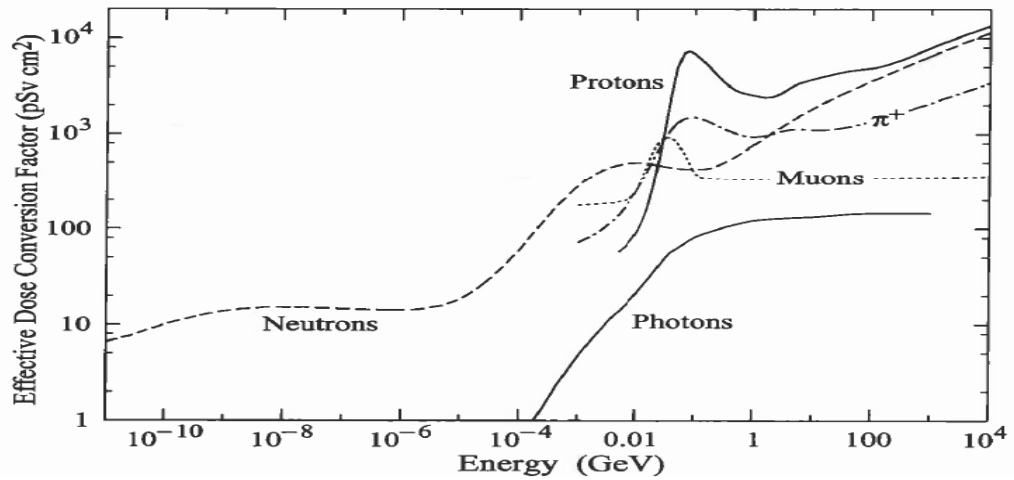
- Intercepted halo power $P_H \cong 2 \cdot (P_{AB} - P_W)$

$$R_n \cong 0.9 \frac{rem}{W\ h}(P_{AB} - P_W) = 0.45 \frac{rem}{W\ h} P_H$$

Comparison with MCNP model

- Convolute MCNP n-energy spectrum with effective dose conversion factor c_n for rad212-p1 detector





- Find $\overline{c_n} \cong 300\ pSv \cdot cm^2 / neutron$

$$R_n = 300\ pSv \cdot cm^2 / neutron \cdot 3400 \frac{neutrons}{cm^2 s \cdot W} P_H = 0.38 \frac{rem}{Wh} P_H$$

- 15% lower than measured value

Beam transmission results

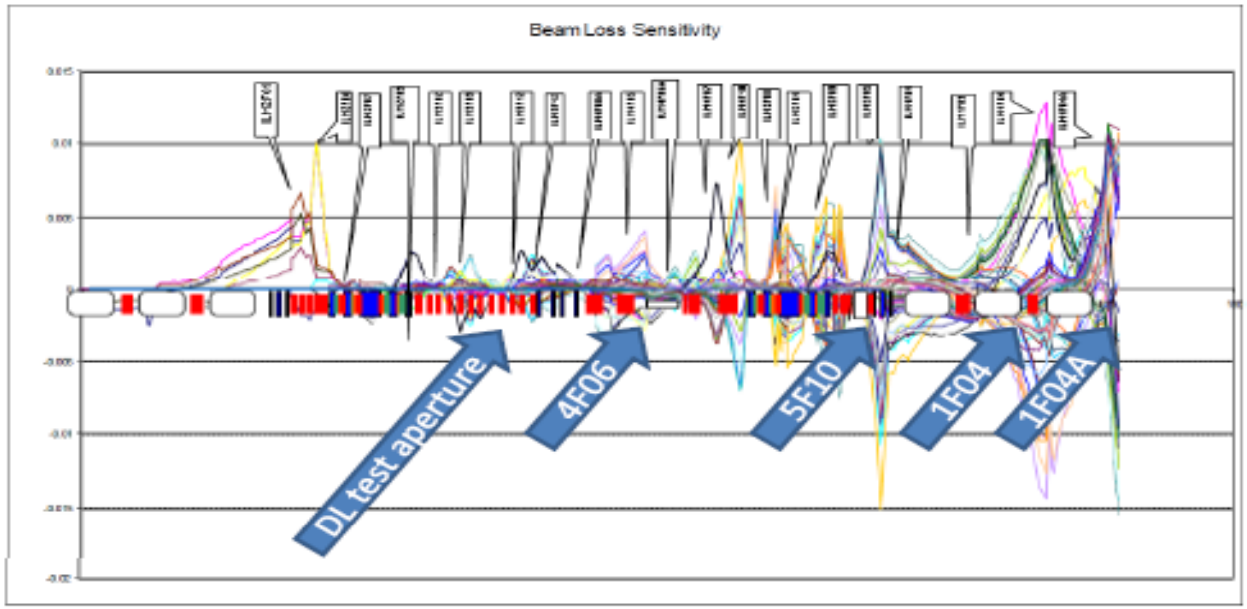
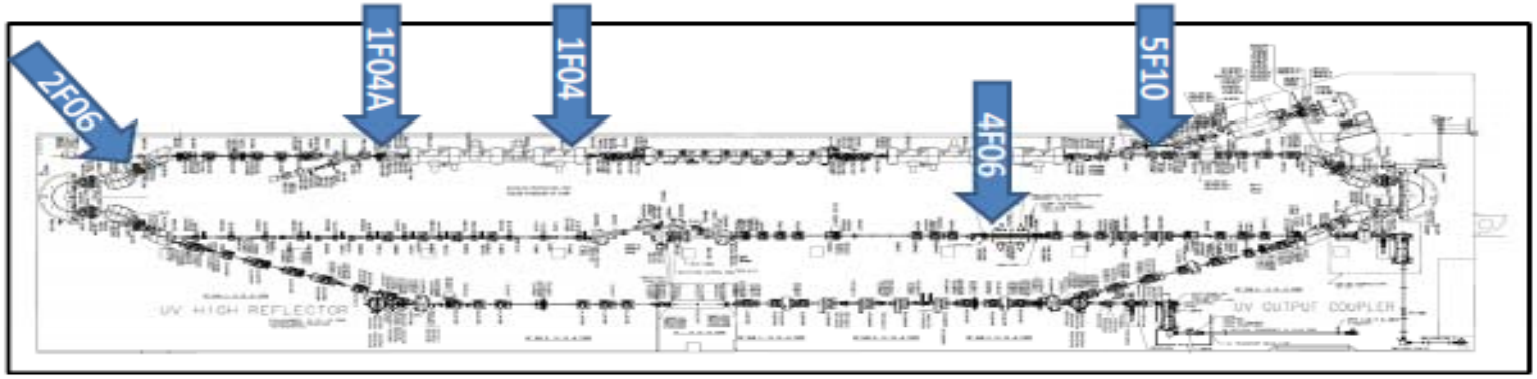
- Power of intercepted beam halo is $P_H = 2 \cdot (P_{AB} - P_W)$
- Power of incident electron beam is $P_b = I_{beam} \cdot 100\,MeV$
- Relative beam loss is P_H / P_b

Run	start	stop	$\Delta T(^oC)$	$T_{ave}(^oC)$	$P_{AB}(W)$	$P_W(W)$	$I_{ave}(mA)$	beam loss
1	13:42	14:03	0.212	31.35	0.332	0.075	3.94	1.3 ppm
2	14:32	15:01	0.719	31.55	0.565	0.10	3.87	2.4 ppm
3	15:55	17:59	10.5	42.6	1.95	0.50	4.25	6.8 ppm
4	10:39	17:32	9.1	44.8	1.09	0.50	4.23	2.8 ppm

Succeeded in passing a 0.43-MWatt electron beam through a 2-mm aperture of 127-mm length with losses of less than 3 ppm.

Back-ups

Loss Maps

projected

observed