Current Measurement and Associated Machine Protection in the ERL at BNL

Toby Miller

Instrumentation Systems Group

Brookhaven National Laboratory

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Description of device

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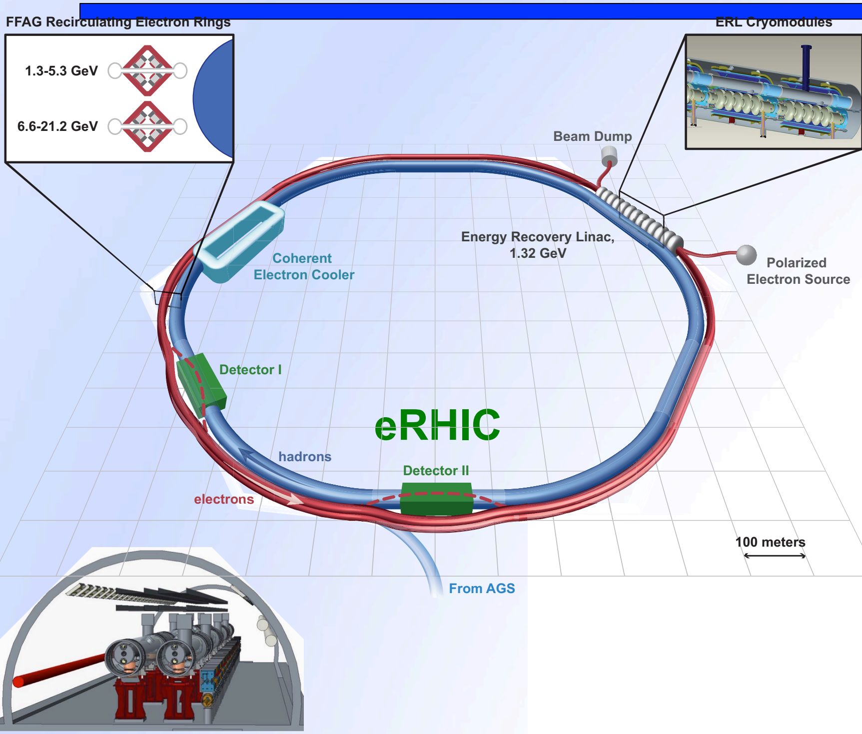
Bunch structures

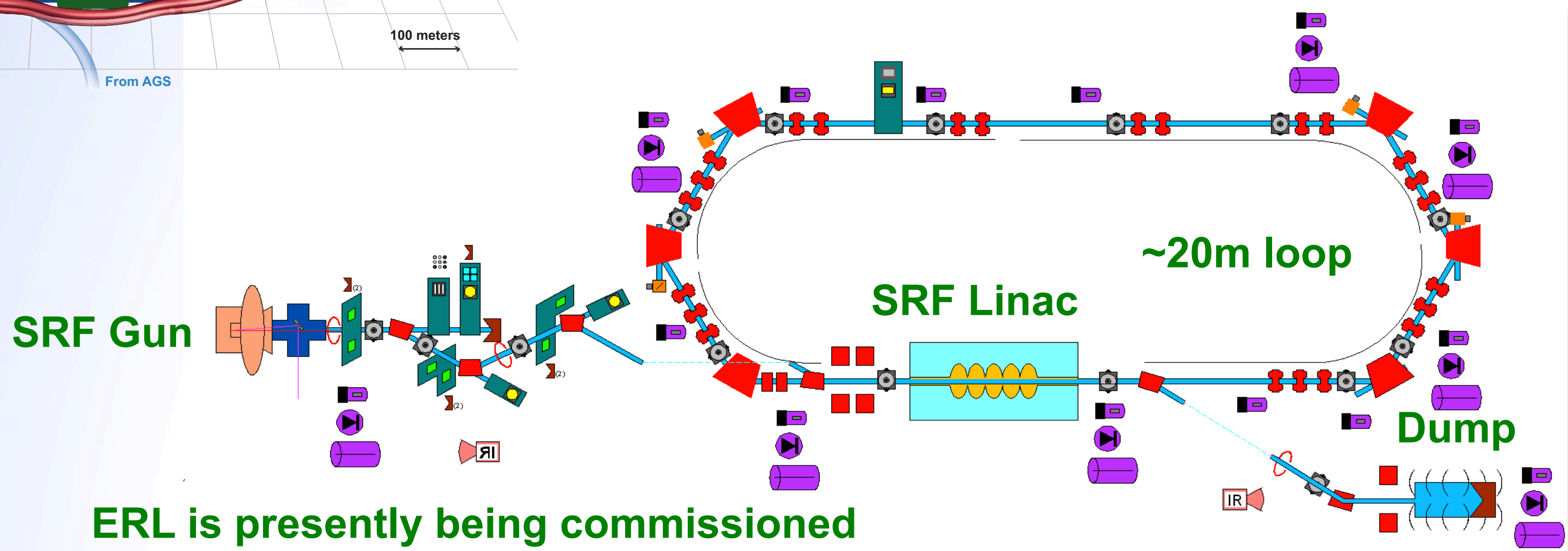
Summary

Introduction



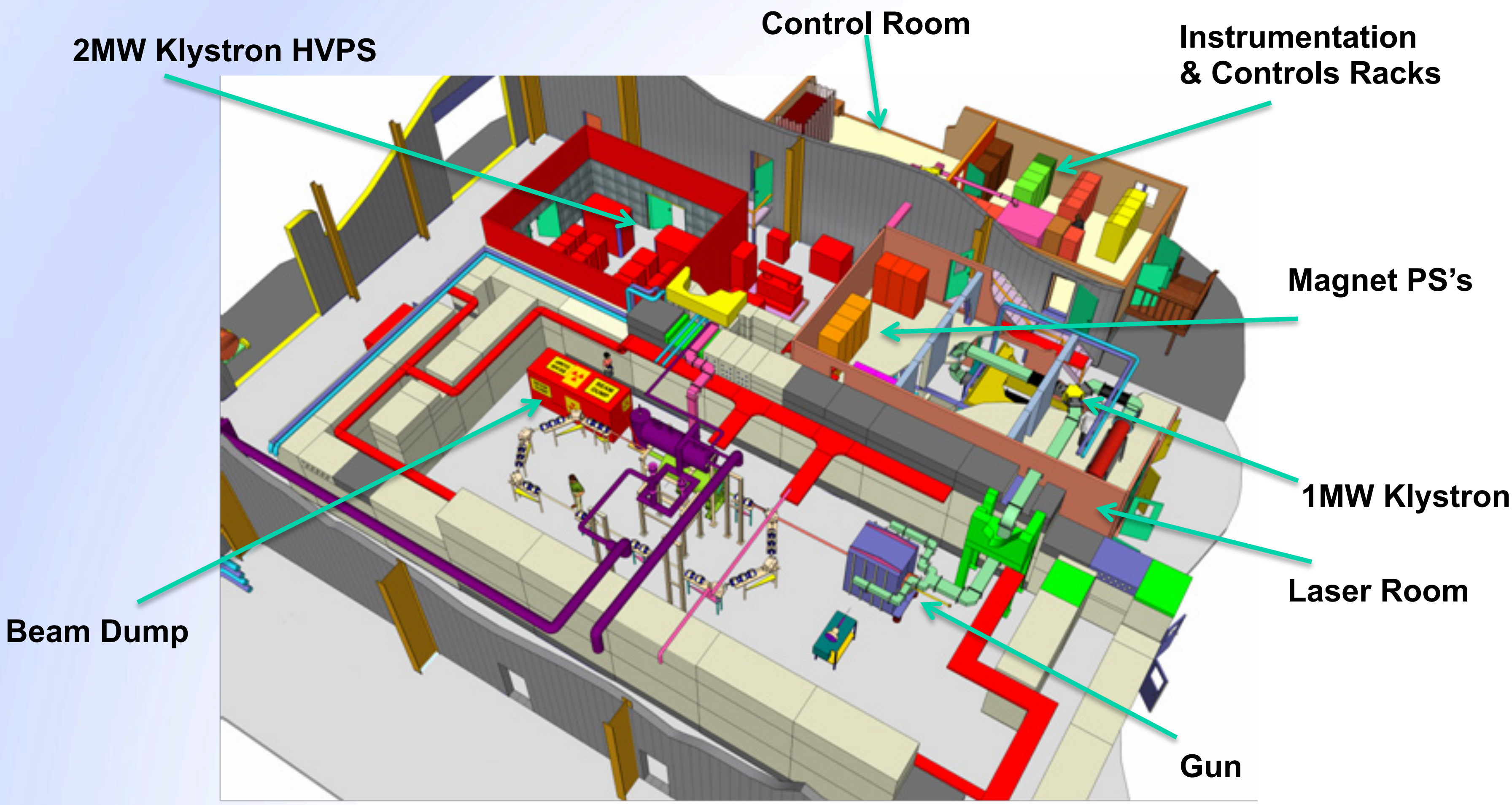
The R&D ERL facility serves a test bed for the Low Energy RHIC electron Cooling and eventually the electron-hadron collider, eRHIC (200GeV, 3.8km).

ERL Instrumentation Layout



ERL is presently being commissioned

ERL Facility Layout



ERL Early Commissioning Parameters

Parameter	High Charge Mode	High Current Mode	Comments
Beam Energy (Injection)	~2.5 MeV		
Beam Current	50 mA	500 mA	
Bunch Charge	0.05 – 5 nC	0.7 nC	
Bunch Rep. Rate	9.38 MHz	704 MHz	
Bunch Length	30ps	20ps	
Car Rep. Rate	5kHz		Limited by integrator recovery time
Car Length	0 – 7 µs (ICT) up to CW (DCCT)		
Train Rep. Rate	1 Hz		
Train Length	0 – 990 ms		

ERL Instrumentation Requirements

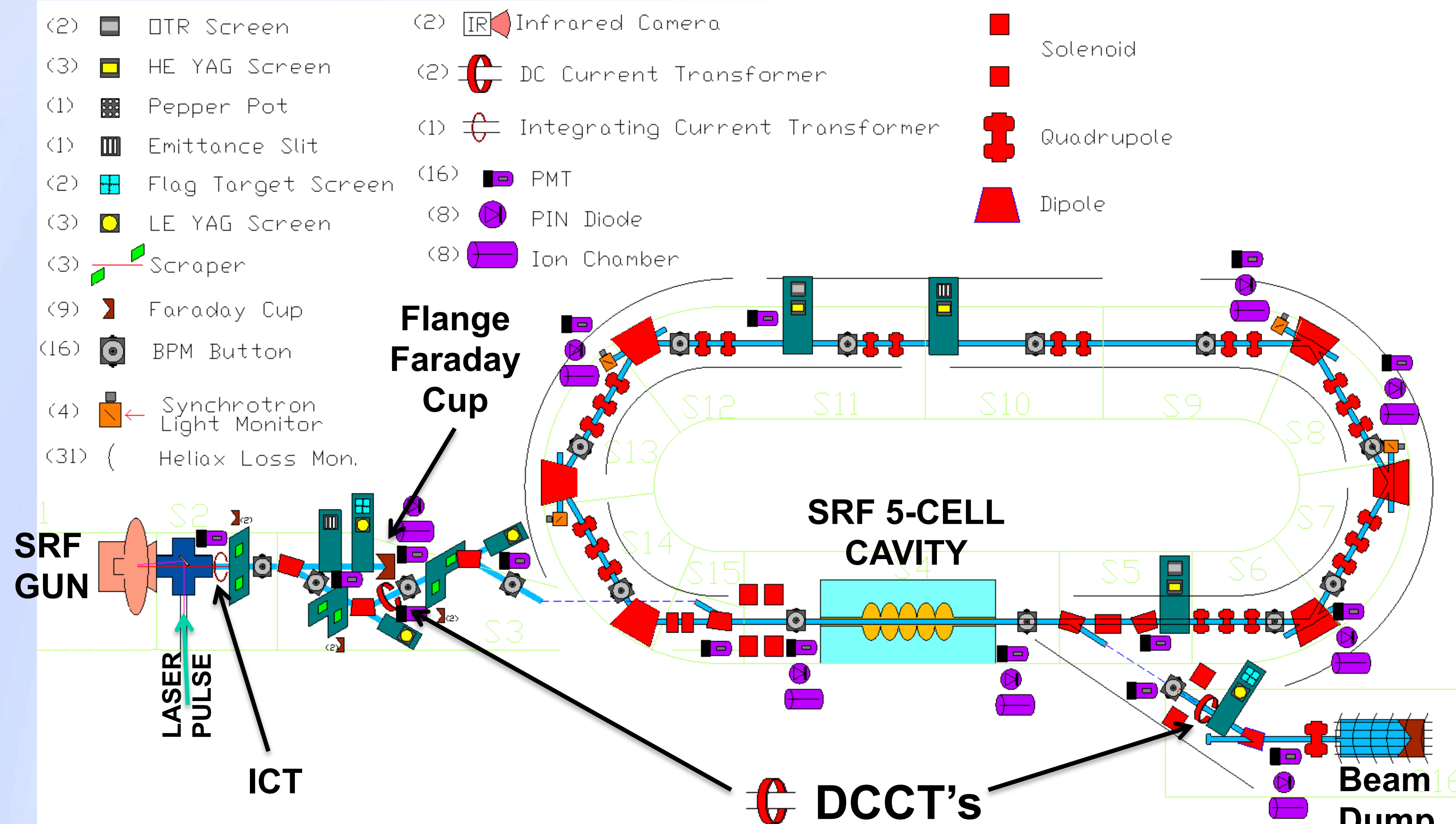
Parameter	Expected Value / Range	Accuracy	Resolution	Comments
Current/Charge per bunch				
Current (Ops.)	50 µA – 500 mA	1%	0.1% at I=500 mA	Lower range needed for tuning.
Bunch charge	0.05 – 5 nC, 1 Hz – 10 MHz	5%	0.1% (at 5 nC)	1% will be sufficient for ERL.

- TWO instruments cover the Measurement Extremes:

  50 pA – 500 mA (1 bunch up to CW)

  - ICT: **50pA – 800µA** (1 × 50pC – 50 × 5nC / 200µs)
    - macrobunhces < 7µs
  - DCCT: **50nA – 500mA** (1000 × 50pC pulsed – Cw_{max})
    - macrobunches > 100µs long in pulsed mode
    - Blind to macrobunches between 7 – 100µs !
    - Can't see beam in diag. beam line !

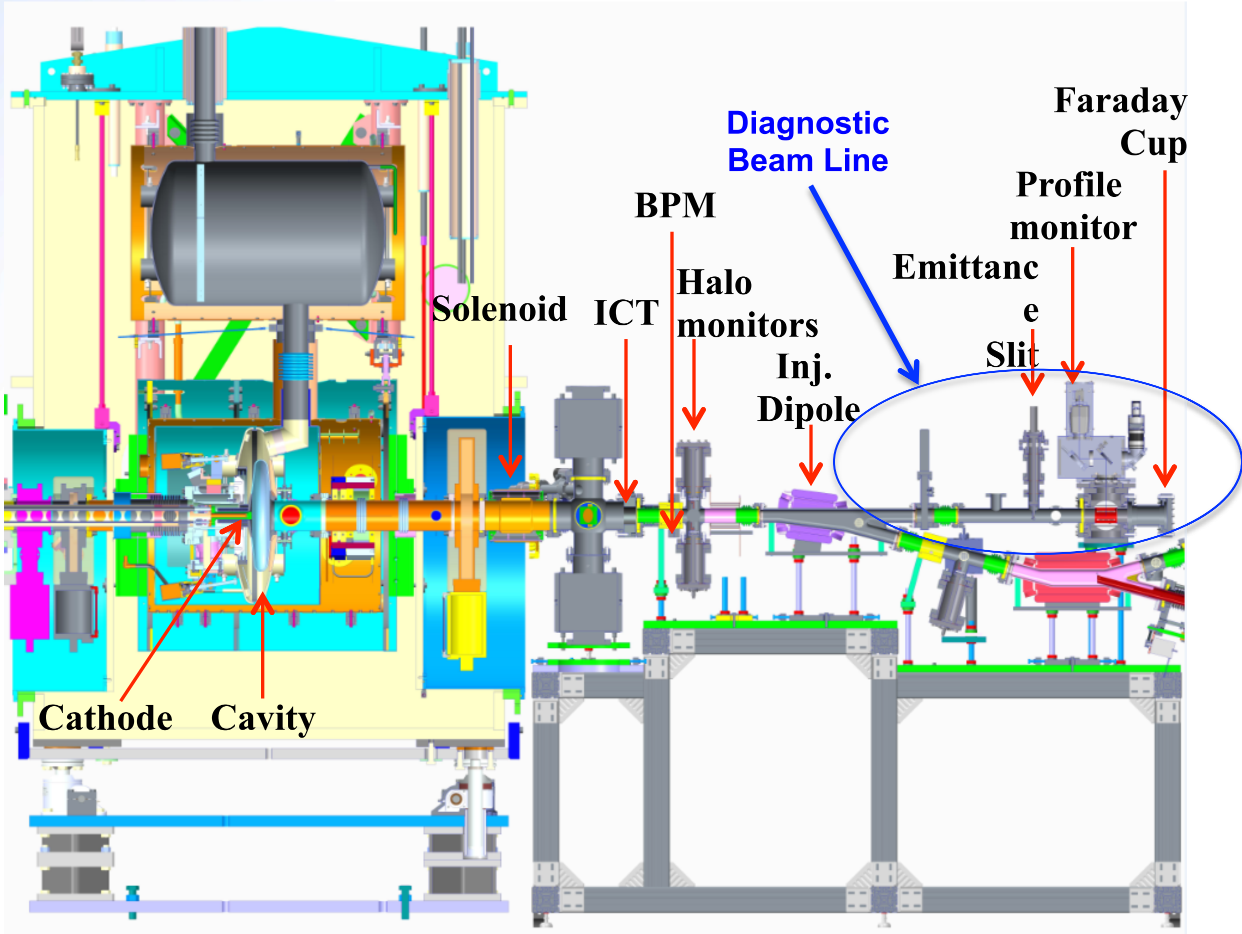
Instrumentation Layout



Injection & Diagnostic Beam Line

- ICT (5:1 turns ratio,~ 6%/μs droop) + BCM-IHR electronics (10kHz)
- BPM
- Scraper
- Emittance Slit
- Profile Monitor
- Faraday Cup

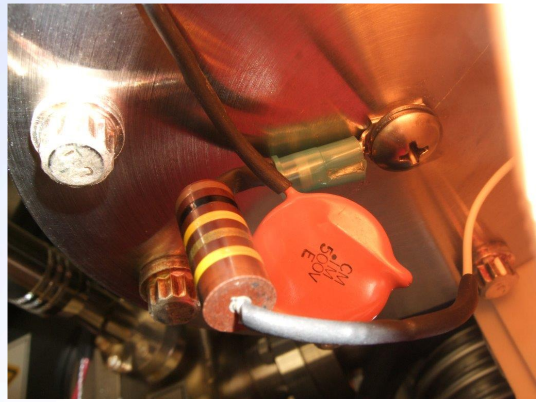
  SS flange on ceramic break with copper mesh noise shield
- DCCTs *(not pictured)*
  - Zig-Zag & Extraction



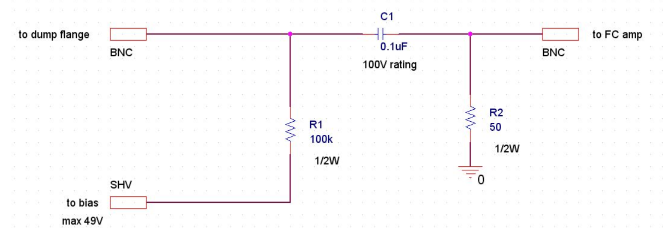
Faraday Cup

- **Faraday Flange**

flange with enclosure to protect from exposure to faraday cup bias voltage

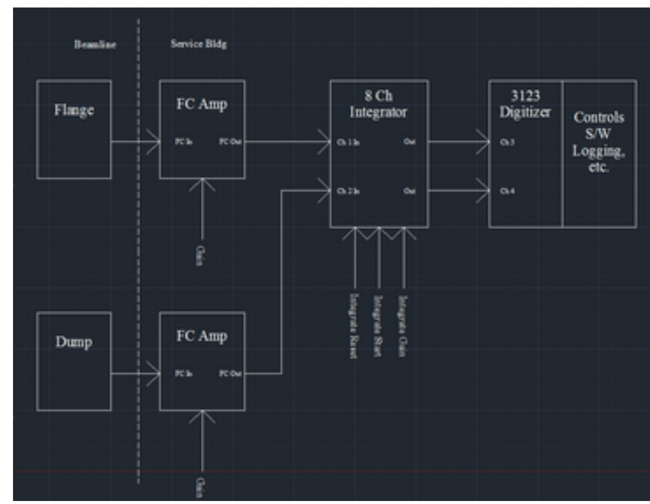


cap/resistor combo on Faraday cup/flange connection



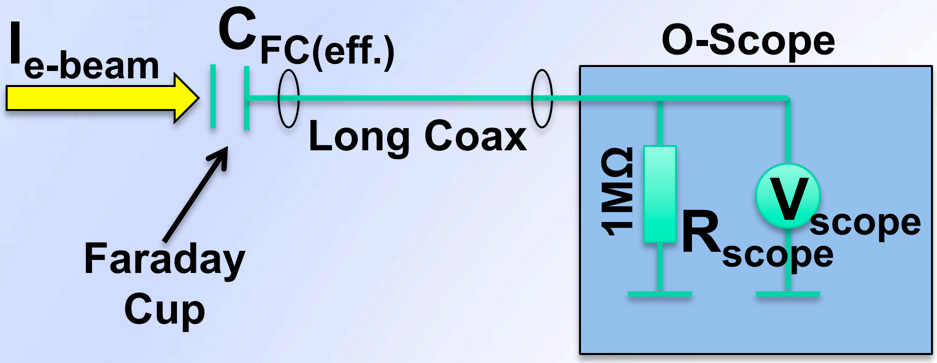
Circuit proposed for bias connection.

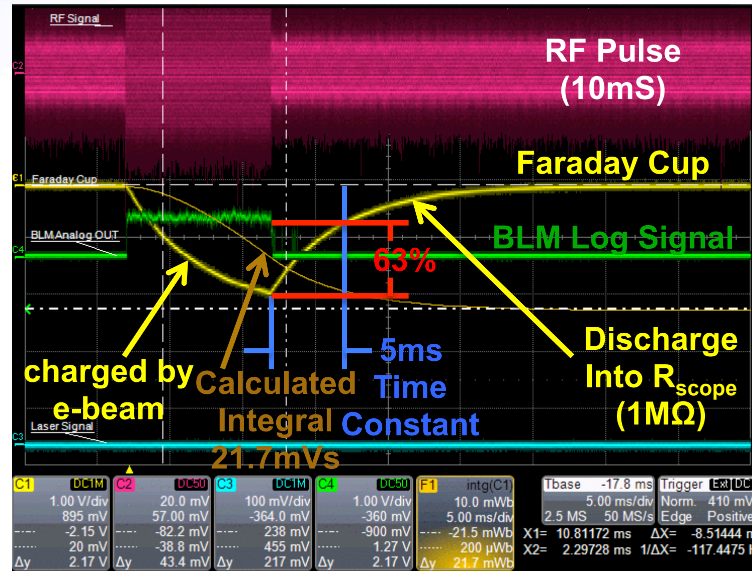
1st beam tests made with O-Scope with direct connection…



Amplifiers & integrators for two faraday cups (plus 6 halo monitors).

Diag. Beam Line Faraday Cup – DARK CURRENT





- Beam Current into Faraday Cup:
  - Finding effective C: [$\tau = RC$]
    - $C_{FC(eff.)}$ = 5ms / 1MΩ = **5nF**
  - We find a Dark Current ≈ **2μA** during the RF pulse from the voltage measured on the effective capacitance of the Faraday Cup.

Dark Current

$$Q = \int I(t)dt = \frac{1}{R}\int V(t)dt$$

$$\bar{I} = \frac{Q}{T} = \frac{1}{RT}\int V(t)dt$$

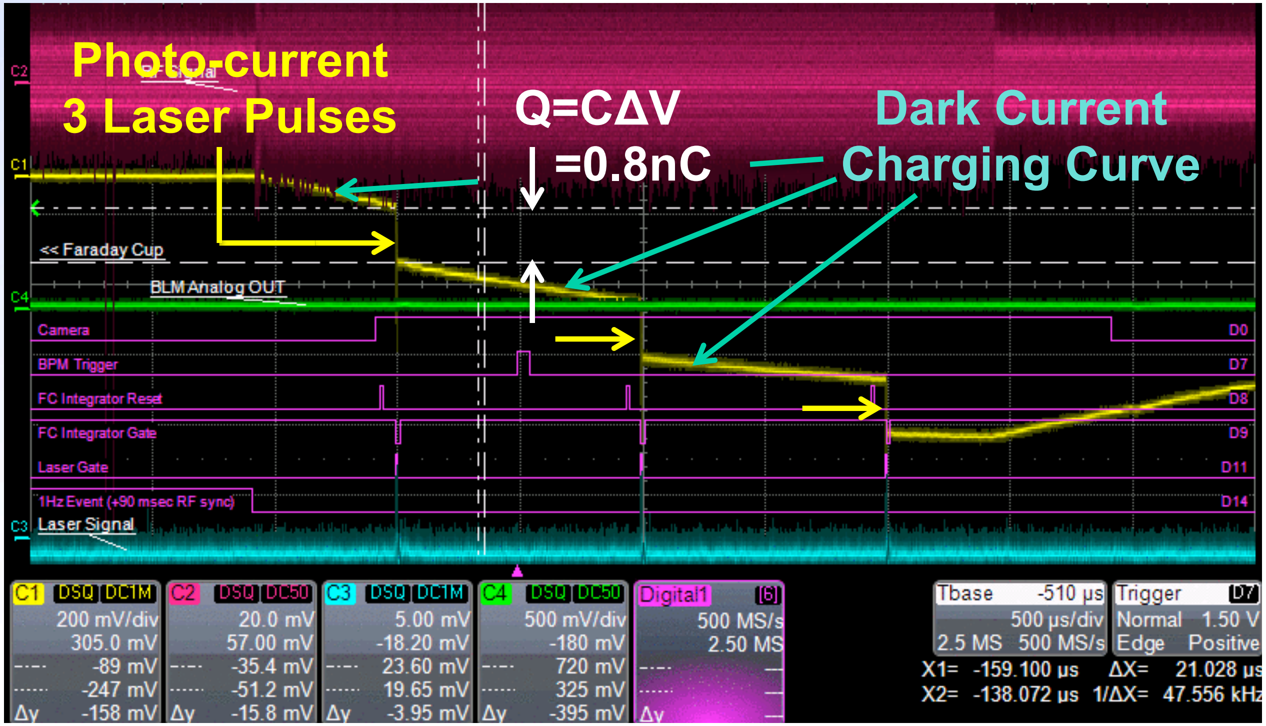
I = 21.7mVs/1MΩ/10ms
= 2.17μA

Diag. B/L Faraday Cup – PHOTO-CURRENT

- ΔV for each beam current pulse gives the charge.
- $Q = C\,\Delta V$

  $=(5nF)(158mV)$

  $=0.8nC$
- Superimposed on Dark Current curve

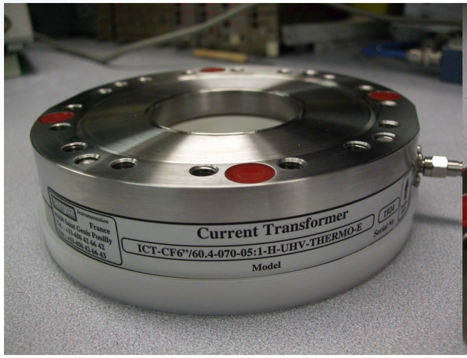


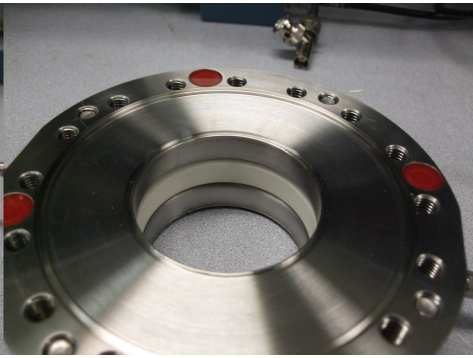
Integrating Current Transformer

<u>**Bergoz**</u> **ICT-CF6-60.4-070-05:1-H-UHV-THERMOE**

Integrating type, In-flange CT

- For bunches bunches & bunch trains
- Bergoz IHR electronics
- Noise <1pC beam charge
- Calibrated





<u>Mechanical details:</u>

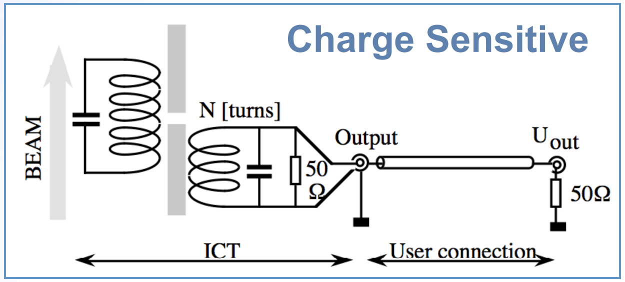
60.4mm ID

40mm axial length

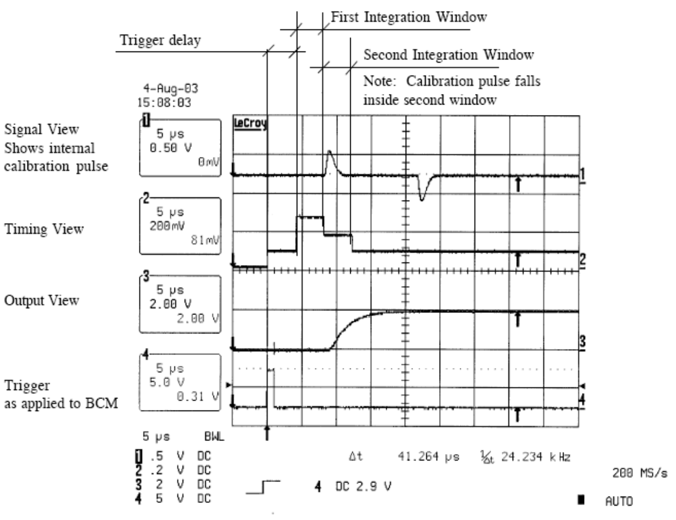
Rad-Hard option

Bakeable to 180C,

- plan 48h at 150C
- Separate bake-out zone
- Internal TC, type-E



Signal processing timing diagram:
Gate width <0.1us up to >7us

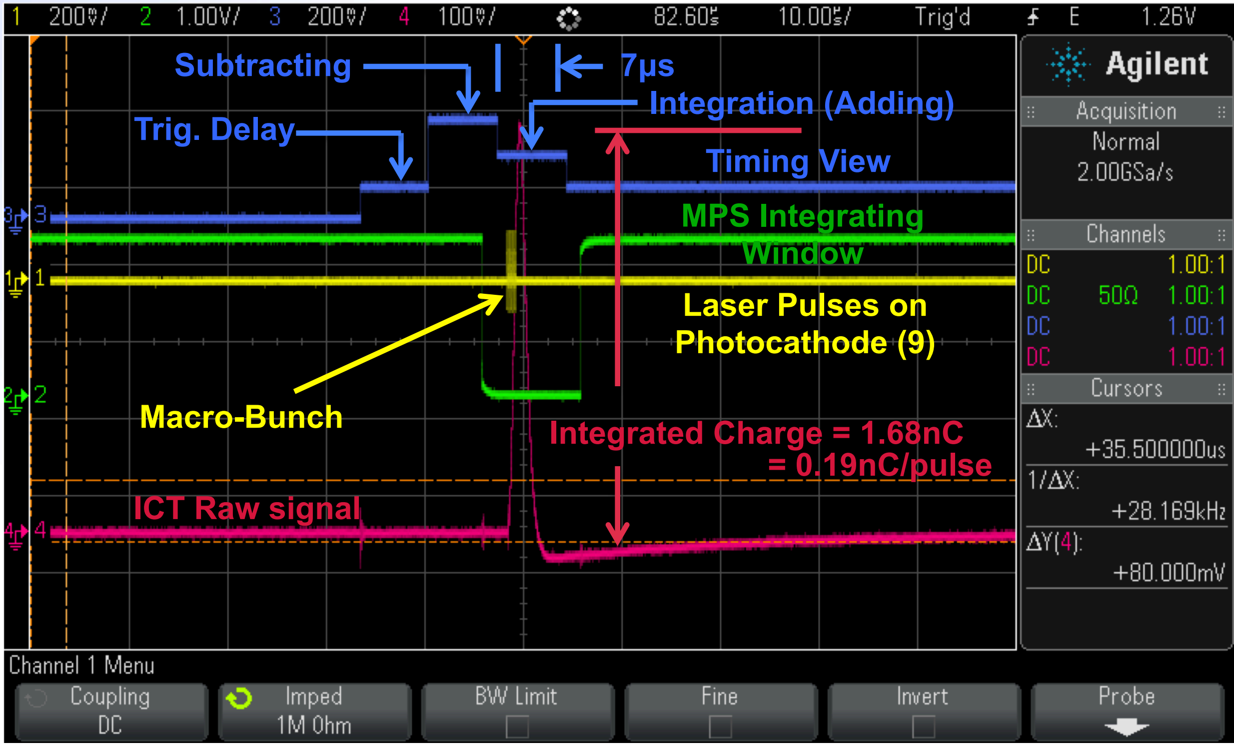


<u>**ERL requirements for bunch charge at 0.1-5nC:**</u>

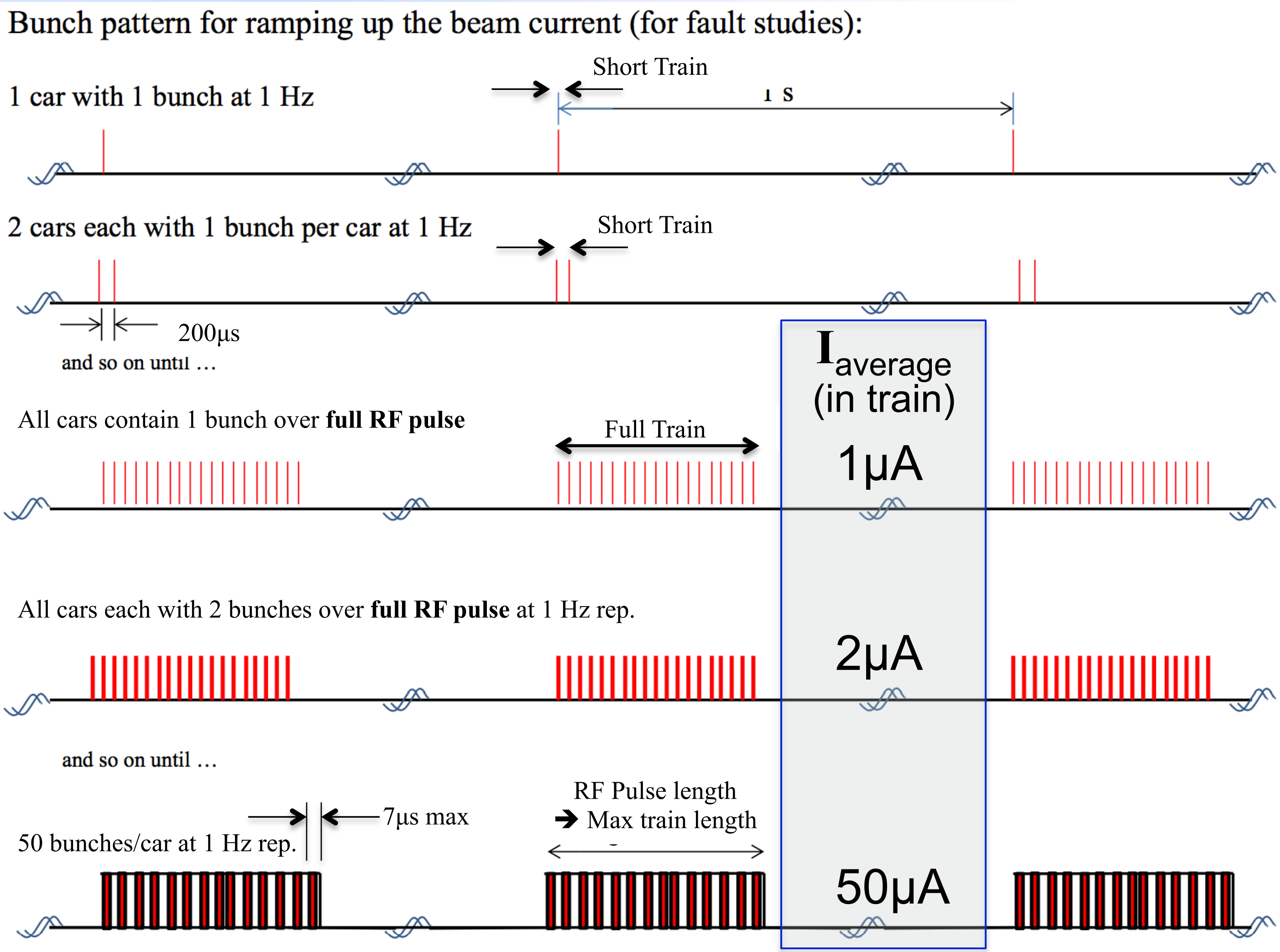
- 5% accuracy
- 1% resolution (at 5nC)

Injection – Integrating Current Transformer

- 7μs Integration window
- 1μs macro bunch
- 9 pulses with 9.38MHz spacing and 44mW
- 1.68nC total charge
  - 0.19pC per bunch
  - (550pC$_{max}$ demonstrated using 4W laser pulses)



Bunch Patterns compatible with ICT



- 200pC/bunch
- 5kHz rep.
- 1 – 50 bunches per car

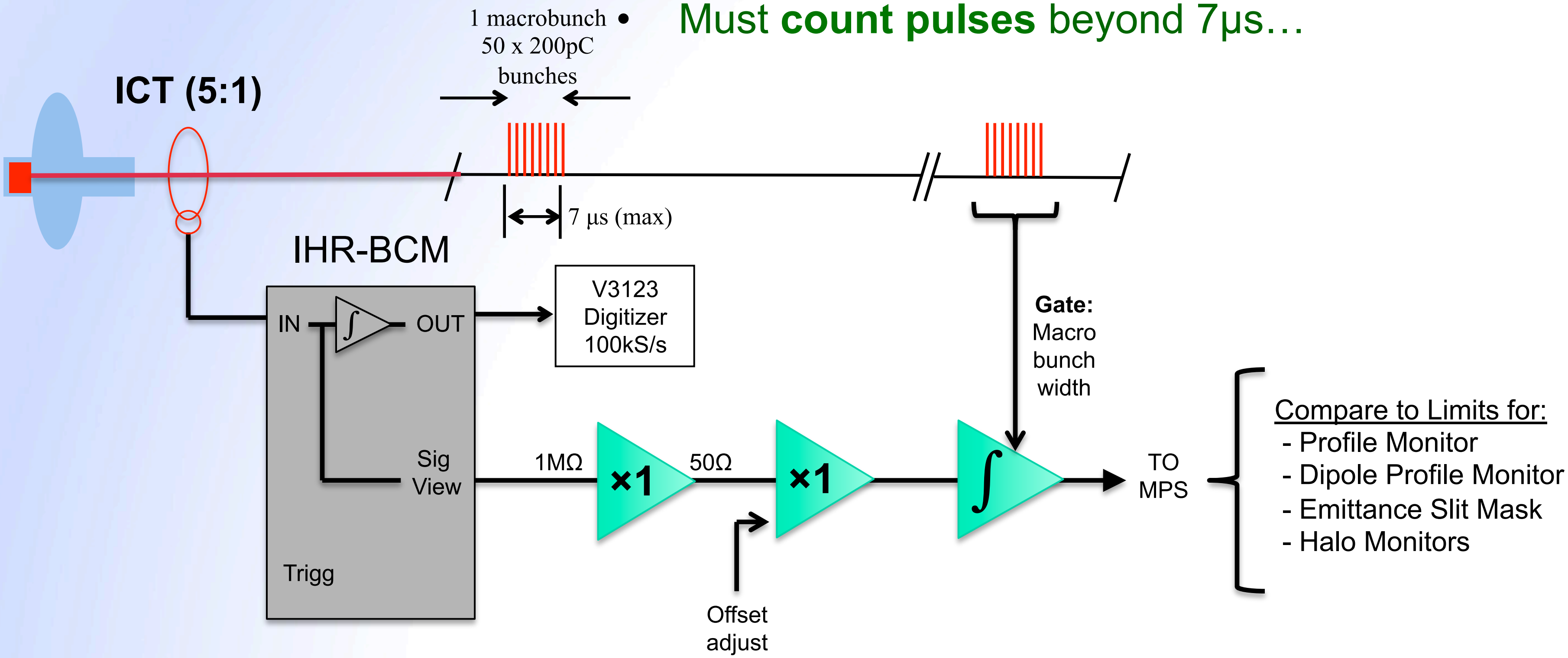
- **ICT**
  - Charge/car
  - 7µs max car length

Machine Protection – Over Current/Charge

- The ICT is used (under limited pulse structures) to:
  - Limit operational current during commissioning & fault studies
  - Log operational current
  - Limit operational current in “Instrumentation Mode”
    - Specific ***charge*** thresholds are set during the insertion of each of the following instruments:
      - Profile Monitor
      - Dipole Profile Monitor
      - Emittance Slit Mask
      - Halo Monitors

ICT interface to MPS

- Dedicated amplifiers & integrators for ICT signal
- MPS compares Charge to limit for inserted device
- Limited to 7μs cars or macrobunches
- Must **count pulses** beyond 7μs…



Pulse Counting Scheme

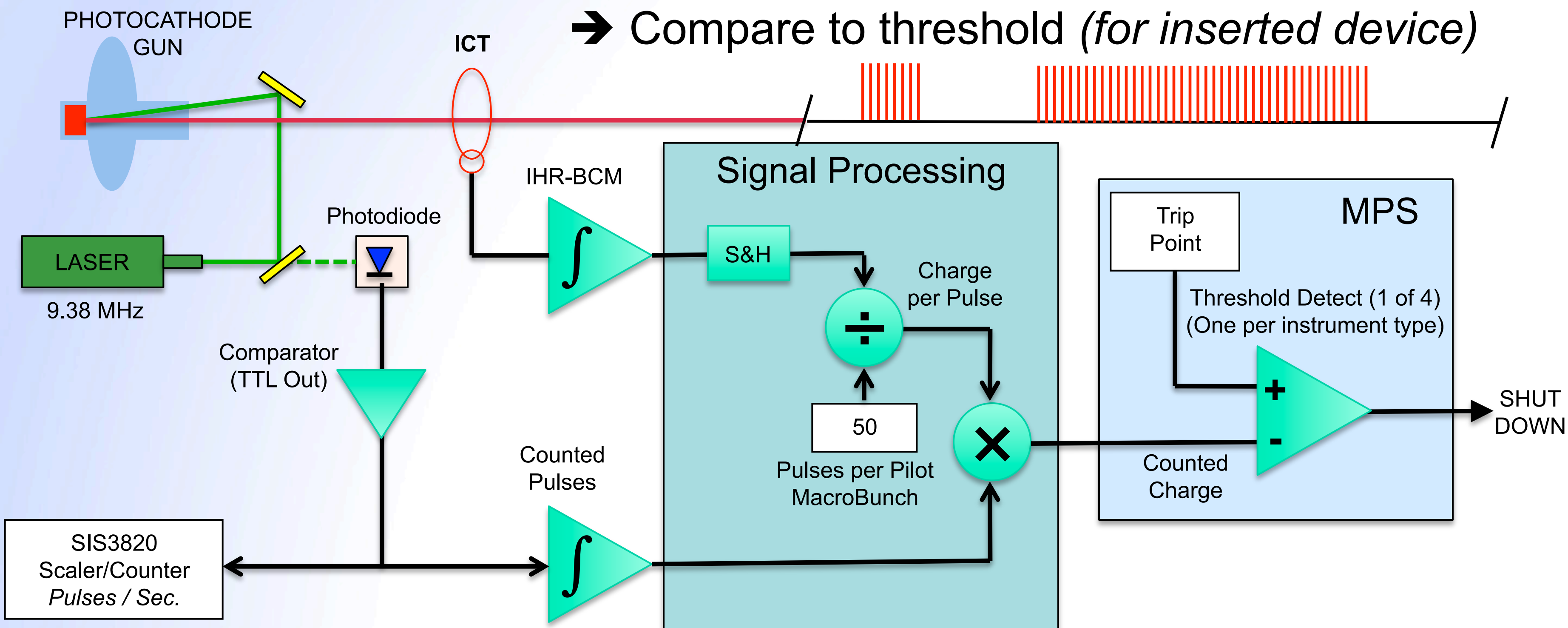
Extending ***charge*** measurement beyond ICT 7μs window

Pilot macrobunch charge measurement

÷ 50 pulses in pilot

× Counted laser pulses

➔ Compare to threshold *(for inserted device)*



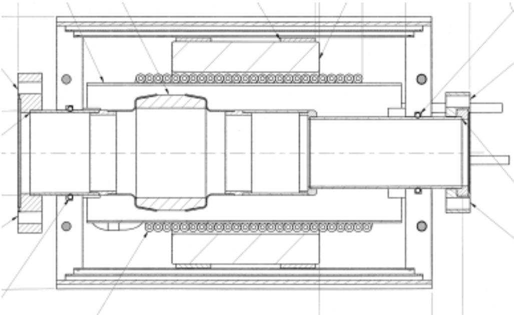
DCCT System

- High precision DC measurement
- DC – 10kHz bandwidth
- ~1uA resolution expected @ 1Hz

<u>Modes:</u>

- Absolute Gun & Dump currents
- Differential Gun – Dump current for Machine Protection (10uA loss budget)

Bergoz NPCT system

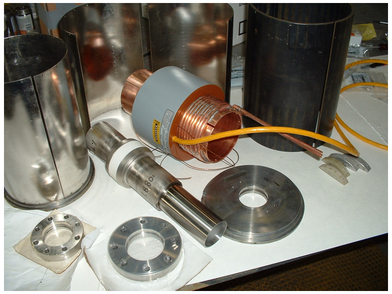


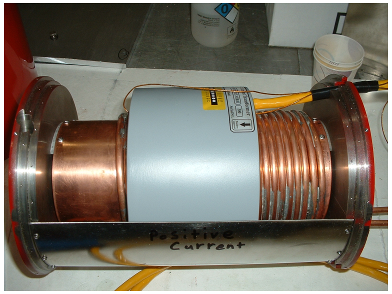
<u>BNL designed enclosure:</u>
Calibration winding
Water cooling (80C max bake)
Mu-metal shield

<u>DIFFERENTIAL SCHEME:</u>
The toroids installed in the injector and dump lines are connected via a current loop that threads both toroids and that is driven by a stable low-noise current source. The current of this source is regulated to minimize the output of the dump toroid. The output of the injector toroid is then the differential current measurement.

Bergoz model # NPCT-S-115 New Parametric Current Transformer, with options:

- 115mm ID
- Very high resolution ($<1uA/(Hz)^{1/2}$)
- Radiation resistant sensor





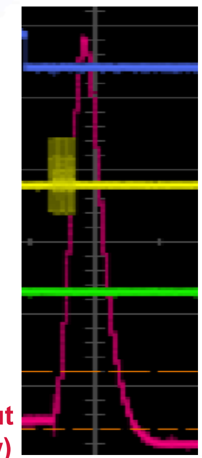
Time response of DCCT vs ICT

- DCCT requires long macrobunches (>100µs)

- Pulse structures tailored for each instrument *(ICT vs. DCCT)*

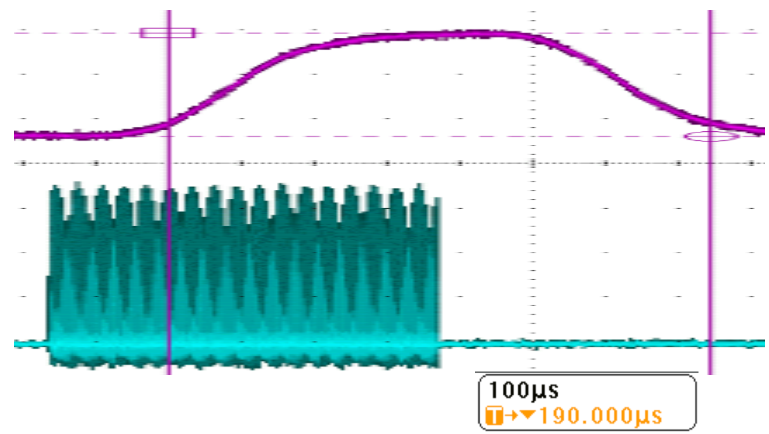
- Instantaneous current measurement for each long macrobunch gives a "pulse current"

ICT Response

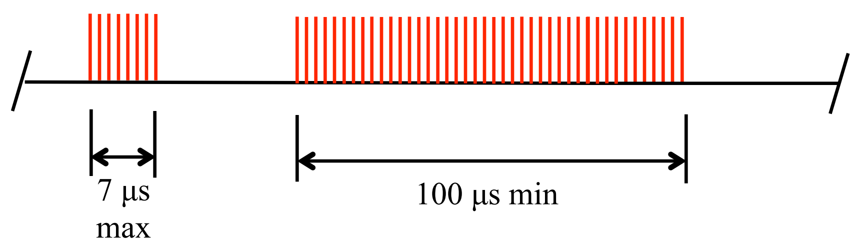


ICT Output (Sig. View)
10µs/div

DCCT Response



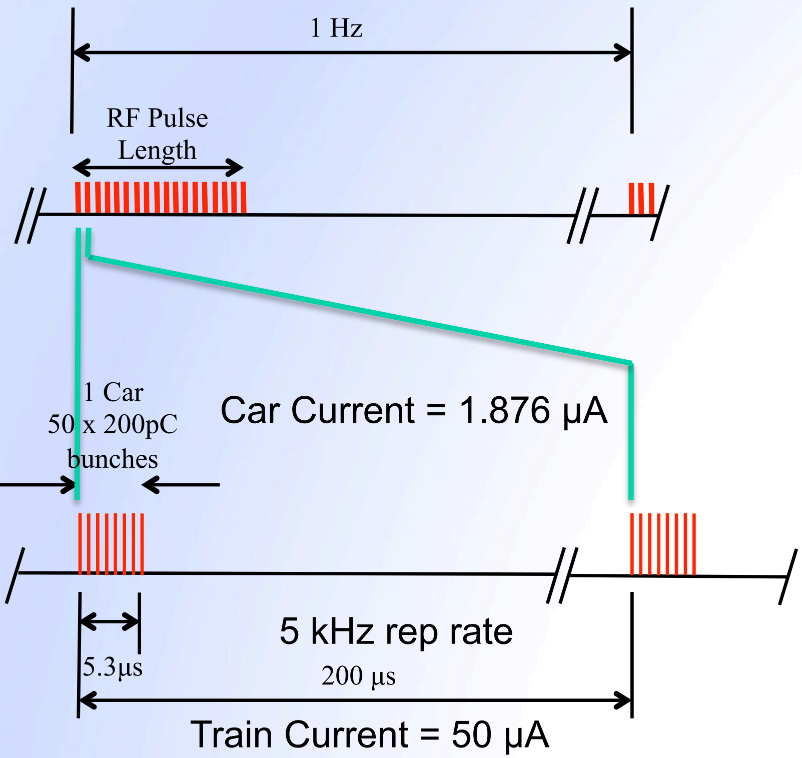
Marcrobunch Widths



Bunch Patterns– ICT vs DCCT

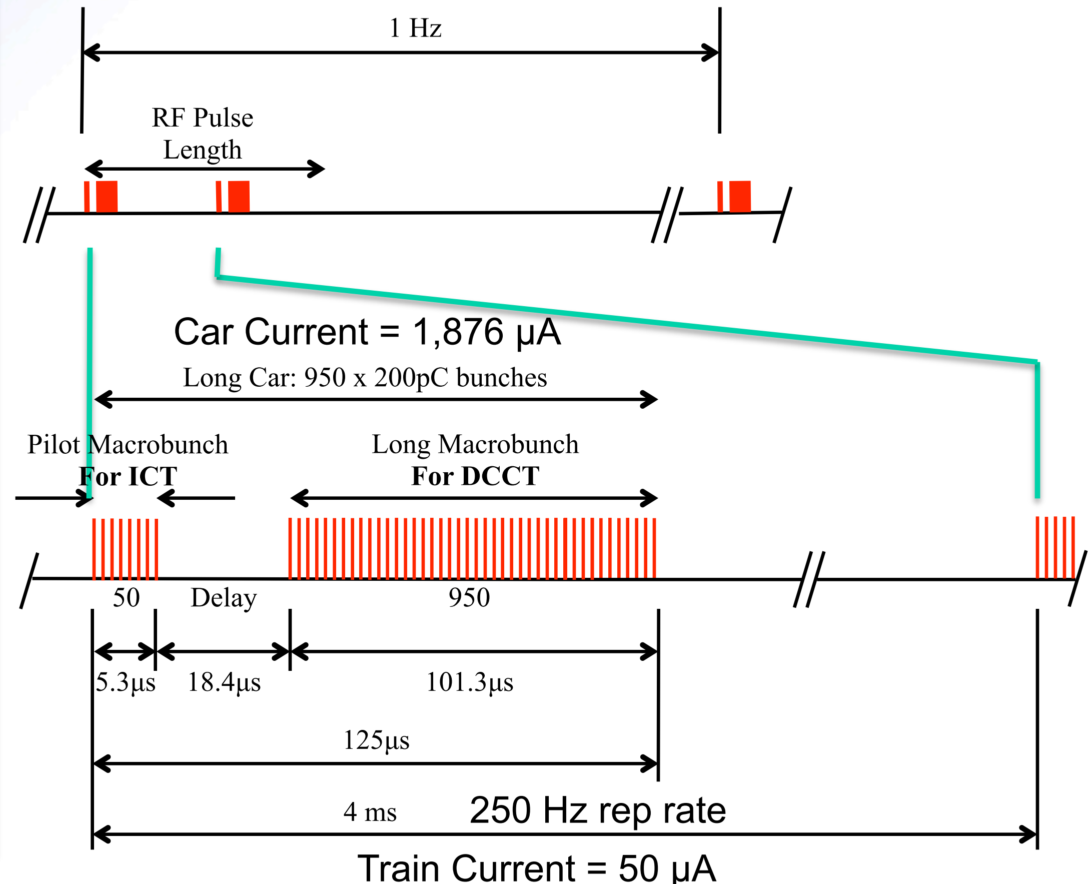
Pulse Structure for ICT

ICT is gated around the Car



Pulse Structure for ICT + DCCT

ICT is gated through the Pilot macro pulse
DCCT is sampled at the end of the Long macro pulse



Summary

- A Bergoz ICT is used to measure beam charge in short macrobunches
  - Up to 50μA average pulse train currents
- Measurements are confirmed with Faraday Cup
- A pulse counter is planned to be used to extend the measurement range of the ICT
- A Bergoz DCCT is used to measure long macrobunches
- Interlock thresholds are set in the Machine Protection System
- Future plans include the use of differential current measurements using separate DCCTs placed near injection and extraction.

Acknowledgments

BNL C-AD

- R&D Energy Recovery Linac Group
- Instrumentation Systems Group
- Controls & Vacuum Group

Bergoz Instrumentation

Thank you for your attention!