RHIC Electron Cooling Diagnostics

Peter Cameron

Outline

- **The ERL**
  - **Machine Parameters**
  - Accelerator Physics **Measurement Requirements -** verify **Machine Parameters**
  - Diagnostics Layout - meet **Measurement Requirements**
  - Diagnostics by system
- The Cooling Section – non-Magnetized Cooling
  - Machine Parameters
  - Accelerator Physics Measurement Requirements
  - Diagnostics by system
- Diagnostics specific to Magnetized Cooling
- Conclusion

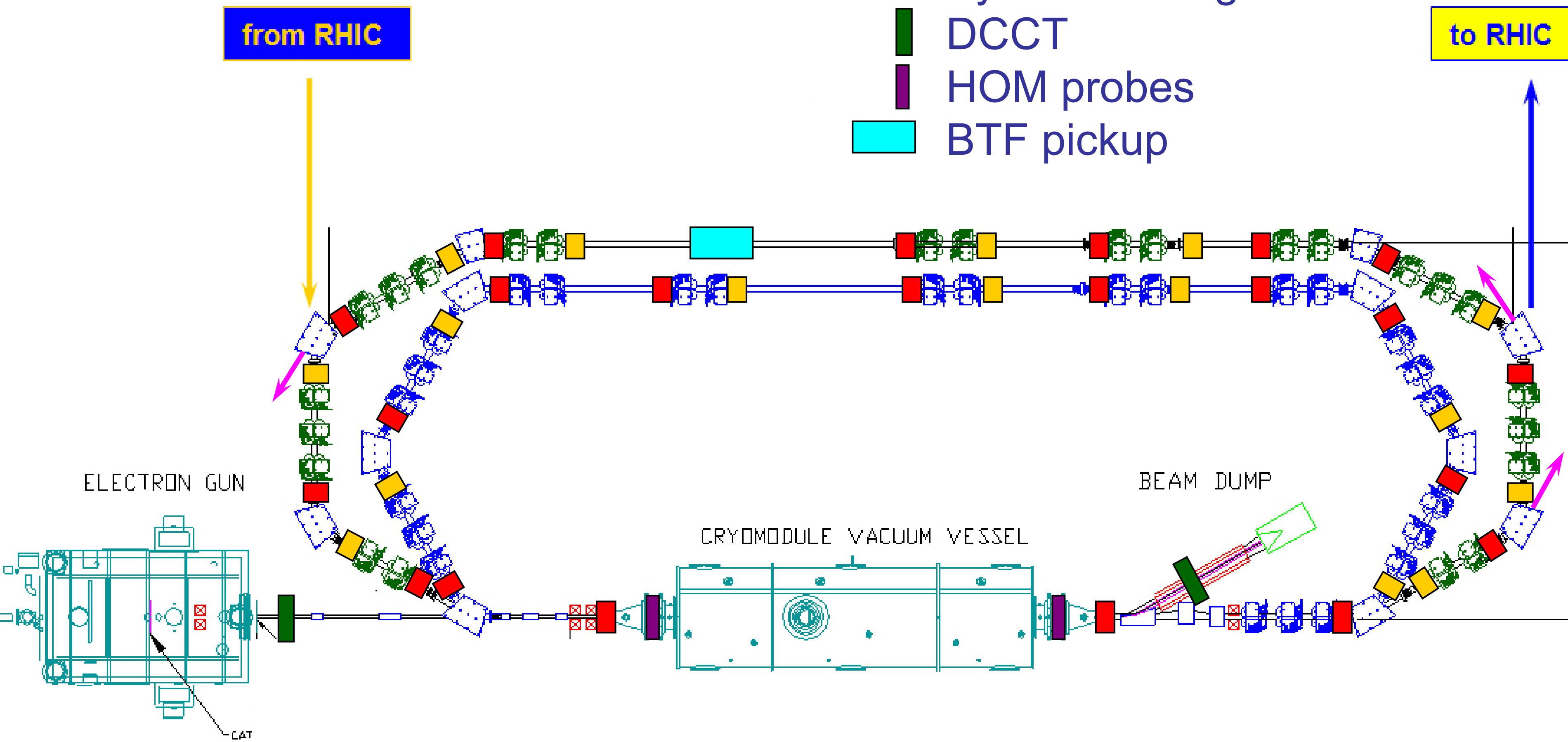
ERL Machine Parameters – non-Magnetized Cooling

Parameter	Value	Diagnostic
injection energy [MeV]	4.7	
maximum beam energy [MeV]	54	spectrometer, Compton,…
rms bunch length [ps]	30	WCM, zero phasing, streak camera,…
RF frequency [MHz]	703.75	
bunching freq [MHz]	9.383	
bunch charge [nC]	5	
average beam current [mA]	50	DCCT
ε_x, ε_y at 4.7MeV [mm-mrad]		Pepper pot
ε_z at 4.7MeV [psec-KeV]		Compton plus streak camera
ε_x, ε_y at 54MeV [mm-mrad]	<5	Synchrotron light, WS
ε_z at 54MeV [psec-KeV]		Streak camera, WS w/ dispersion
rms dp/p	10^{-3}	
energy recovery [%]	99.95	Cavity power
current recovery [%]	99.9995	Differential current, loss monitors

ERL Diagnostics Devices and AP Specifications

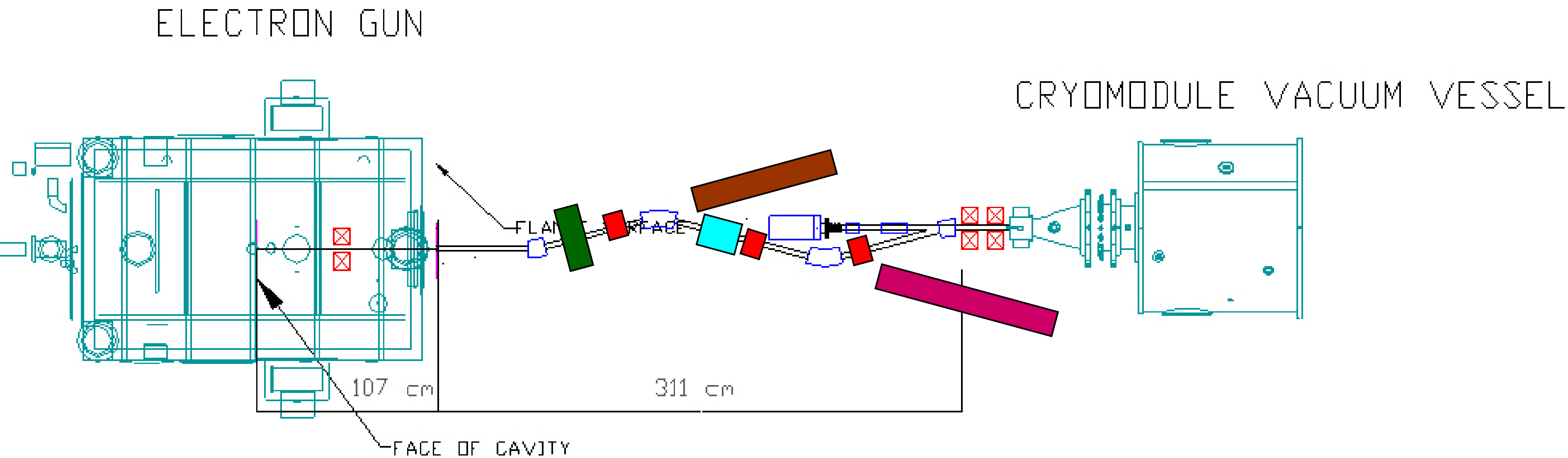
Device	Qty	Range	Accuracy	Resolution	Comments
Position/Phase					
BPM (button)	25	1/2 pipe rad	100μ	1μ (av)/5μ	Dual plane
Phase	25	+/- 180 deg	+/- 2 deg	0.2 deg	BPMs w/ I/Q
HOM probes	6				Mini-CF antennas
BBU/Transfer Function	1				kicker, sample scope,...
Beam Energy	2		$2x10^{-3}$	10^{-3}	Spectrometer, Compton
Loss					
BLM (PMT)	20	1-1000 rem/h	30%	0.5 rem/h	20msec and 1sec
		10^{2}-10^{5} nA-sec		50 nA-sec	damage at ~10uA-sec
Current					
Current	25		5%	1%	BPM sum signal
Current	2		1%	0.1%	Bergoz PCTs
Differential	1	10^{2}-10^{5}nA-sec	$5*10^{-6}$	$2*10^{-6}$	2 toroids w/ null
Profile					
Crosses(flags,wires,…)	16				
Wire Scanner - profile	2	Full aperture	0.2σ		SEM mode
Wire Scanner - halo	2			10^{-6}	BLM mode
Synchrotron Light	3		0.2σ		At bend magnets
Energy Spread	-		10^{-4}	10^{-5}	Not day one

ERL Portion of RHIC eCooler



ERL Injector Portion of RHIC eCooler

Legend:
- DCCT
- Button BPM
- Pepper pot
- BTF kicker
- Compton/Streak



Elevation View

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e^- Beam Diagnostics – Position

Calculated Electronics Performance	
Parameter [units]	**value**
bunch charge [nC]	5
bunch length [psec]	30
Button voltage [V]	260
Cable loss [dB]	2.6
RF filter voltage [V]	1.8
IF filter voltage [V]	0.5
Thermal noise [μV]	3
Losses [dB]	7
Amp noise figure [dB]	4
Contingency [dB]	6
Resolution [μm]	5 < 1 w/avg
Phase resolution [deg]	< 0.1
Current	5×10^{-4} $< 10^{-5}$ w/avg

proven

- **Buttons - LHC 24mm design**
- **Electronics - SNS design morphed to VME**
    - Calibration - via S21 thru the PUE
    - BP filter at 703.75MHz RF
    - phase-synchronous mix to 28.15MHz/2 and 10MHz bandpass filter
    - phase-synchronous digitize at 28.15MHz x 2 – gives I/Q demodulation
    - sum signal for current
- Absolute position
    - survey - a few hundred microns
    - BBA - tens of microns
- Phase calibration
    - $dx = (4r/3)(dp/p) \sim 0.2m$

      where $r \sim 0.2m$, $dp/p \sim 10^{-6} \sim 0.1$ degrees

    Sweep phase, note maximum beam deflection, calibrate within the required 2 degrees

e^- Beam Diagnostics – Loss

- AP current recovery spec is 99.9995%
  - at 50mA requires **~0.2μA accuracy**
- Damage threshold (loss pattern is important)
  - ~10 μA-sec at 54MeV
  - ~100 μA-sec at 4.7MeV
- Sensitivities at 54MeV:
  - PMT/scintillator BLMs ~.01 μA-sec (blind spots?)
  - Cable BLMs ~0.1 μA-sec (blind spots less an issue?)
  - Differential current DCCTs ~0.1 μA-sec or better?
- Sensitivities at 4.7MeV:
  - Loss monitors on the edge of being marginal?
  - Differential current particularly helpful here

e^- Beam Diagnostics – Current

Current measurement

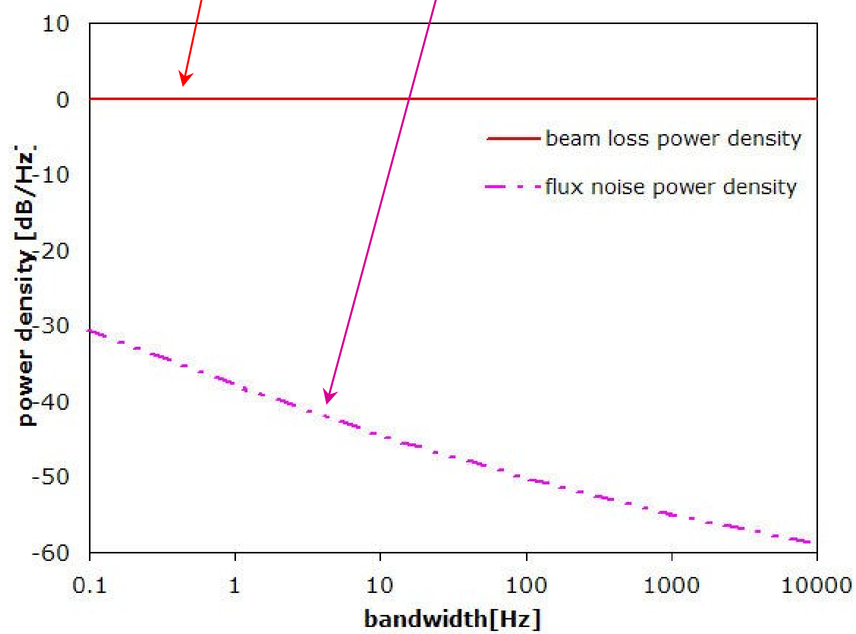
Bergoz 'new' PCT

resolution ~20μA with 40mA beam

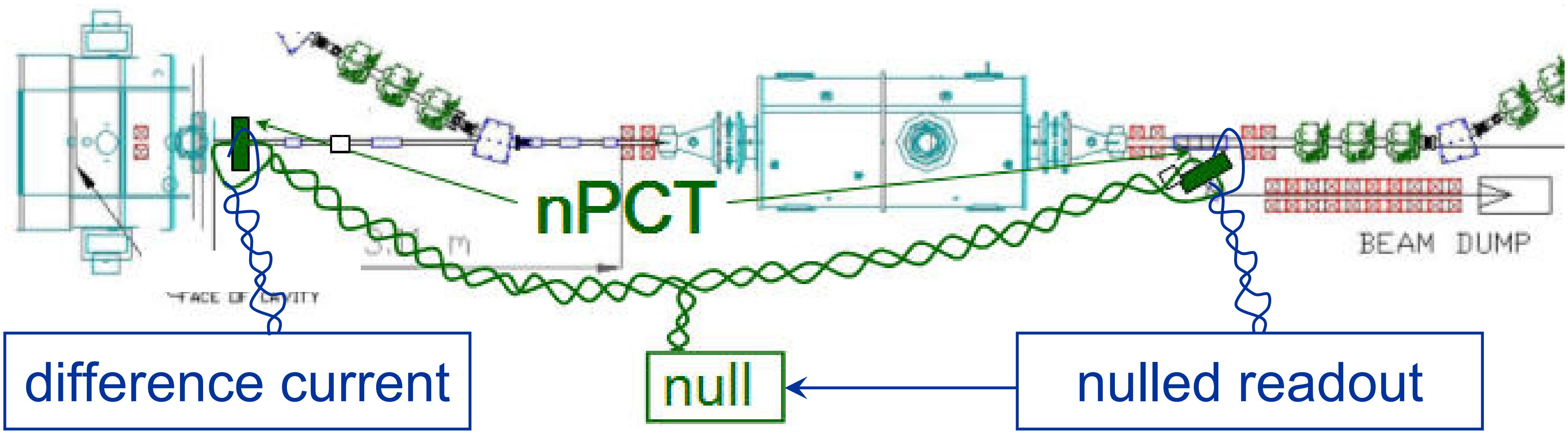
Differential Current

- PCTs linked by nulling winding, null beam current to gain dynamic range
- Frequent no-beam calibration for drifts
- Noise sources (uncorrected)
  - flux (Barkhausen) noise ~0.1mA/rtHz, 60dB above thermal
  - gain/linearity ~1ppm/mA
  - spurious field ~100mA/G
  - temperature ~5mA/K

Removed by nulling



Differential Current Measurement



utilizes nulling to attain ~ 10^{-6} resolution:

- DCCTs calibration windings are joined by a single loop, powered by a low-noise current source, driven opposite the beam
- Output of Dump DCCT is fed back to current source, to drive Dump DCCT output to zero
- Output of Gun DCCT is then the differential current measurement
- Drifts (thermal, gain, magnetic field) removed by nulling w/o beam

Proposal submitted in response to HEL-JTO BAA 05-DE-01

P. Cameron, “Differential Current Measurement in the BNL ERL”, C-A AP Note 203

e^- Beam Diagnostics – Profile

- Wire Scanners - avoid proximity to SRF (cavity damage)
  - limited to <~10μA beam current for full profile
  - dynamic range ~ 10^6 or better gives good halo monitor
  - disadvantages - special mode, wire breakage, welded bellows,...
- Flags - again, avoid proximity to SRF if possible
  - dump line - for zero-phasing bunch length measurement?
- **Synchrotron Light**
- Streak Camera
- Differential Current
  - Halo control is crucial
  - high resolution, non-interceptive,...

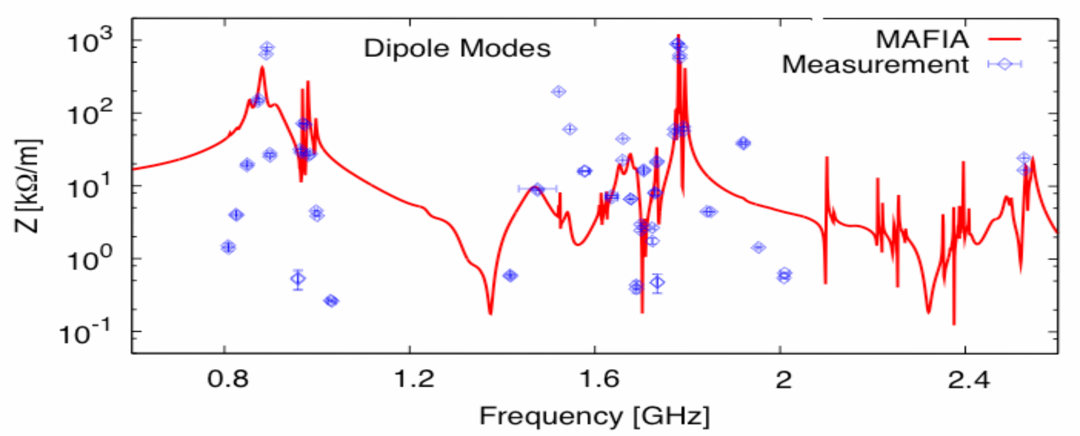
Beam Diags – HOM/BBU/BTF

HOM monitors

- 3 antennas in CF flange between cavity and absorber - both ends of SRF
- gate to eliminate direct pickup of bunch signal

Beam Transfer Function

- stripline kicker and pickup
  - null at ~1.3GHz
- excite, explore HOMs
- also excite with
  - longitudinal fill pattern?



BBU monitors - timescale ~1msec

- BTF pickup with fast scope (also longitudinal profile monitor)
- Buttons with synthesized LO, BBU specific gate array code?
  - First filter is the problem

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RHIC eCooling Parameters

Parameter	Value	Diagnostic
Ion beam energy [GeV/A]	100	Dipole current and Magnet Transfer Function
initial rms dp/p	10^{-3}	Schottky, WCM
initial rms bunch length [ns]	1.2	WCM
RF frequency [MHz]	197.043	
bunching freq [MHz]	9.383	
bunch charge [nC]	15	WCM
average beam current [mA]	150	DCCT
initial rms ε_x, ε_y [mm-mrad]	2.5	IPM, Schottky, Luminescence
cooling section length [m]	60	
cooling section β_x, β_y [m]	>200	

Parameter Comparison

RHIC eCooling Parameters	
Ion beam energy [GeV/A]	100
initial rms dp/p	10^{-3}
initial rms bunch length [ps]	1200
RF frequency [MHz]	197.043
bunching freq [MHz]	9.383
bunch charge [nC]	15
average beam current [mA]	150
initial rms ε_x, ε_y [mm-mrad]	2.5

ERL Machine Parameters	
electron beam energy [GeV]	.054
rms dp/p	10^{-3}
rms bunch length [ps]	30
RF frequency [MHz]	703.75
bunching freq [MHz]	9.383
bunch charge [nC]	5
average beam current [mA]	50
rms ε_x, ε_y at 54MeV [mm-mrad]	<5

Cooling-specific Diagnostics Devices and AP Specifications

Device	Qty	Range	Accuracy	Resolution	Comments
new					
Relative velocity					
Ion Velocity	2		$2*10^{-3}$	10^{-3}	spectrometer-based
e^- Velocity	2		$2*10^{-3}$	10^{-3}	Compton and spectrometer
Cooling optimization					
Recombination monitor	2	1KHz-1MHz		counting mode	Scraper + PMT, based on 24hr recombination lifetime
Relative Position					
Fast BPMs - ions and e^-	4	½ pipe radius	5μ relative	1μ	WCM-style, simultaneous measurement of ions and e^-
Button BPMs - ions and e^-	120?	½ pipe radius	5μ relative	1μ	With ions and e^- de-phased, located every meter?
existing					
Emittance - ions					
ZDC	4		5%	1%	Requires ion beams in collision
IPM	4		10%	3%	Both planes, both rings
Schottky	12		20%	1%	distribution dependence??? 2GHz, 245MHz, and 1.7GHz TW
Momentum spread					Ions only
WCM	2		5%	1%	Both rings
Schottky	6		10%	1%	2GHz, 245MHz, and 1.7GHz TW

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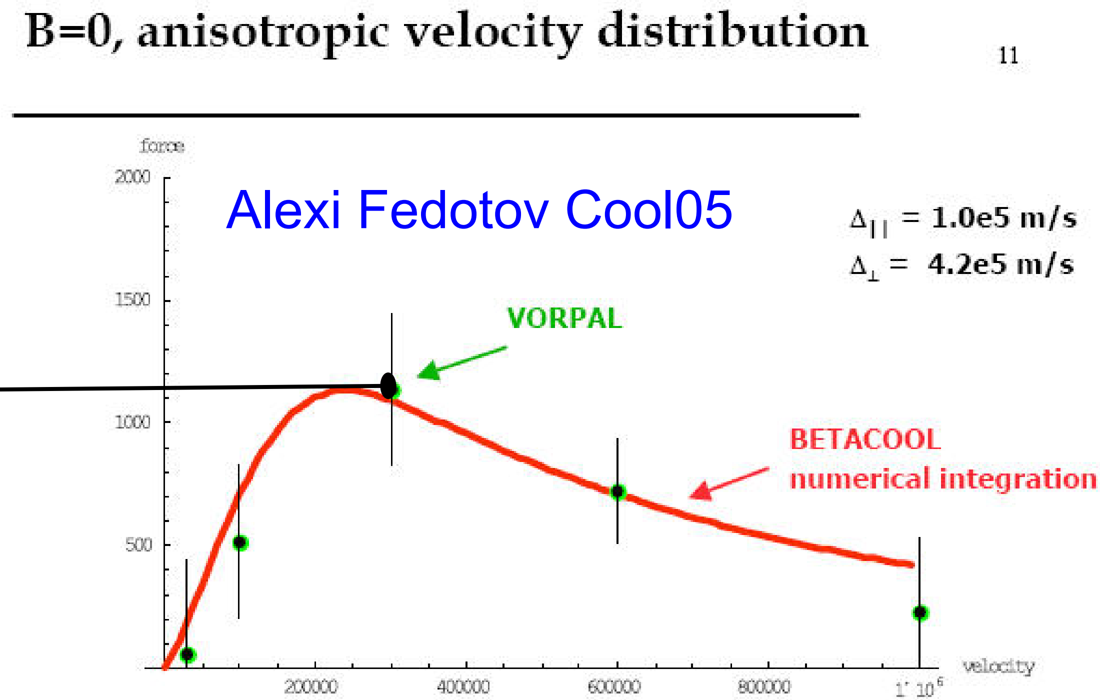
Cooling Diagnostics – Velocity Match

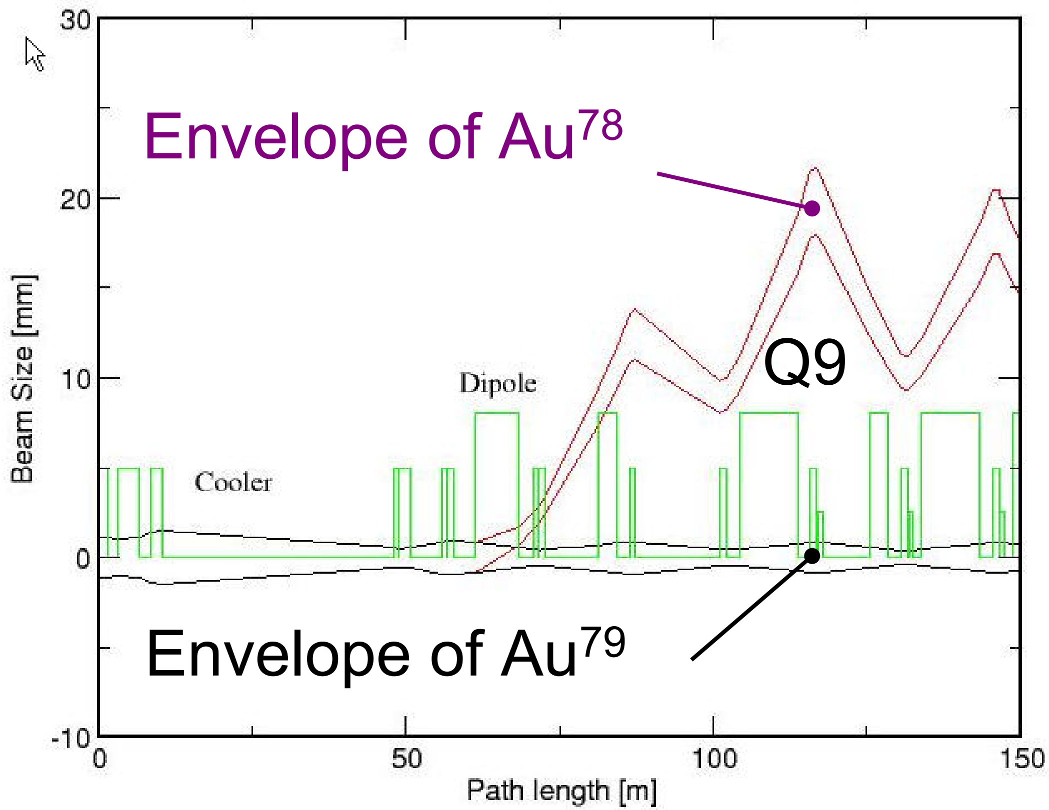
- The idea – get match good enough to permit using recombination monitor for fine tuning
- Assume δv in Ion frame of 3×10^5 m/s
- In lab frame this is 30m/s – can't measure
- Energy difference is $(\gamma_e - \gamma_I)/\gamma_e \sim 10^{-3}$



- This can be measured via 'magnetic spectrometer'
  - LEP and SLAC experience ~ 10^{-4} with big effort
  - at RHIC we just need magnet current and transfer function
- e^- beam energy can also be measured by Compton cutoff

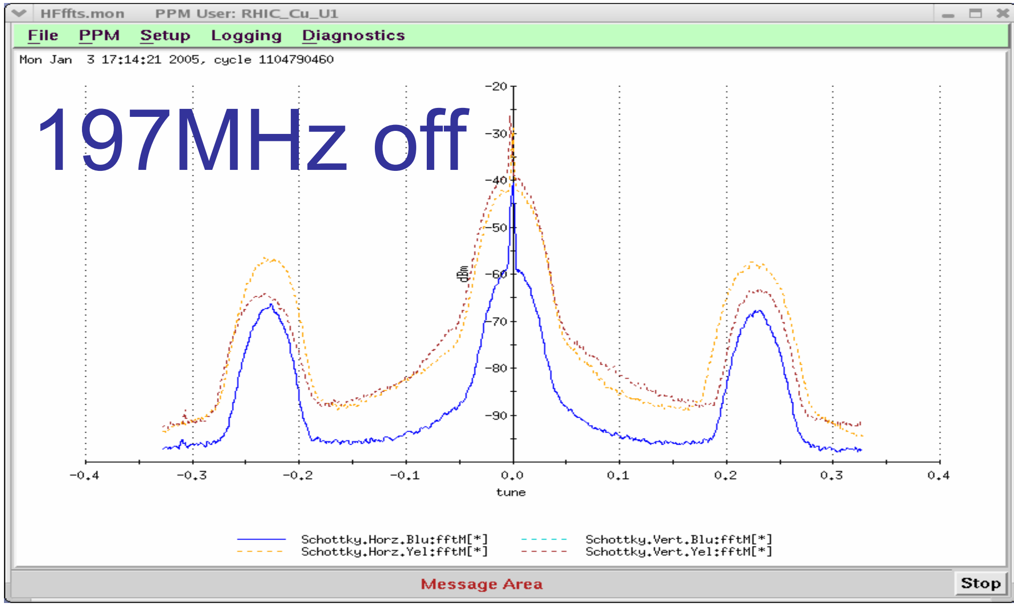
Cooling Diagnostics – Recombination

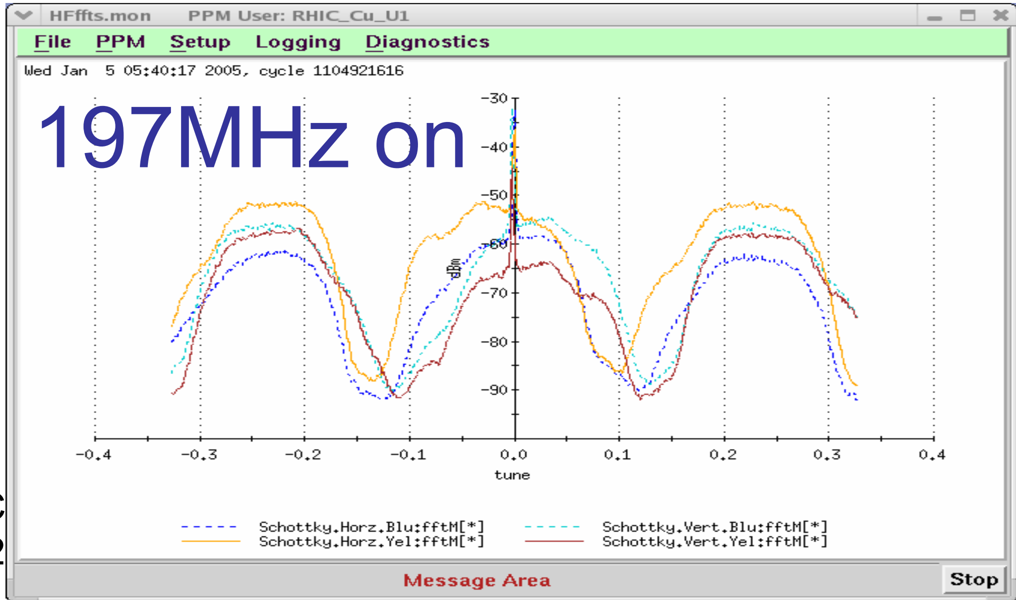
- Use recombination monitor for more sensitive tuning
- With recombination lifetime of 1 day and 10^{11} ions in RHIC, then rate is 1MHz.
- Would like at least tens of Hz to start tuning, limit will be background?
- Scraper plus PMT at Q9 (region of large displacement)



Cooling Diagnostics – Schottky

- Three existing systems
  - 2GHz resonant
  - 245MHz resonant
  - 1.7GHz TW
- Can measure emittance and momentum spread with high resolution (Z=79, I=150mA)
- Need refinement of calibration methods
- Need improved understanding of how to properly interpret non-Gaussian profiles





Cooling Diagnostics – fast BPM

- Need to monitor relative transverse positions of Ion and electron beam along the length of the cooling section
- Broadband BPM – segmented fast Wall Current Monitor
  - Functions as both WCM (sum signal) and BPM (difference signal)
  - Bandwidth limit ~6GHz – marginal for 70ps bunches

CLIC WCM

Biconical WCM/BPM

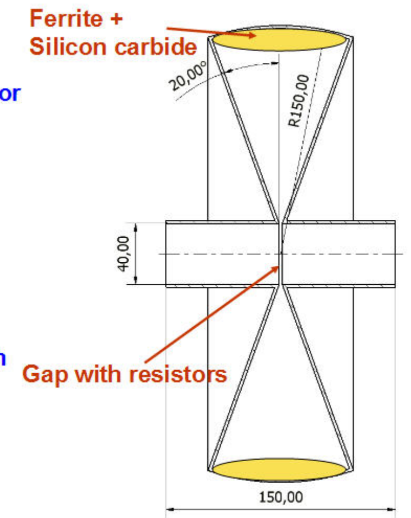
Fritz Caspers

- prototype fabricated and tested at CERN
- 3dB BW ~7GHz without ferrites/absorbers

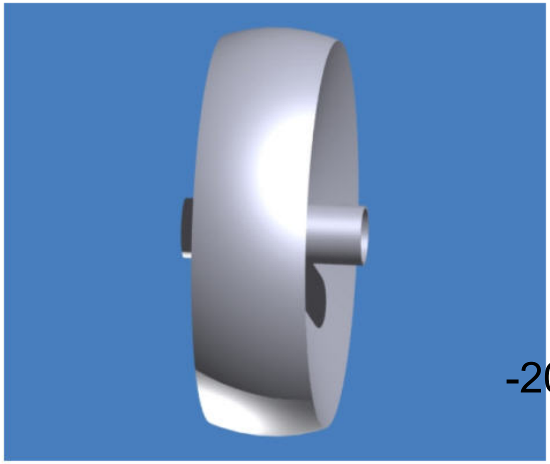
A "biconical" WCM

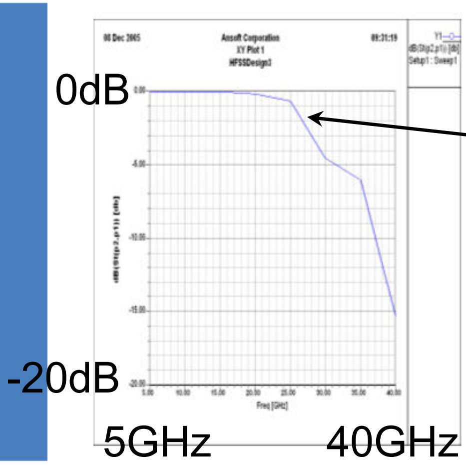
- An idea (Biconical antennas or radial transmission line) by F. Caspers.
- Guides radial spherical TEM wave which is absorbed by Silicon carbide and ferrite.
- No corners to avoid HOM conversions.
- Should have higher bandwidth than traditional tank shapes .
- Optimize angle to gap impedance.

$$Z_{Cone} = \frac{377}{\pi} \ln(\cot \frac{\varphi}{2})$$



"Biconical" WCM





Transmission (S21) simulation of 50ohm setup, but done without absorbing boundary.

- Calculated (HFSS) 3dB point ~25GHz
- Conventional WCM is ~6GHz
- Optical fiber signal path

stics

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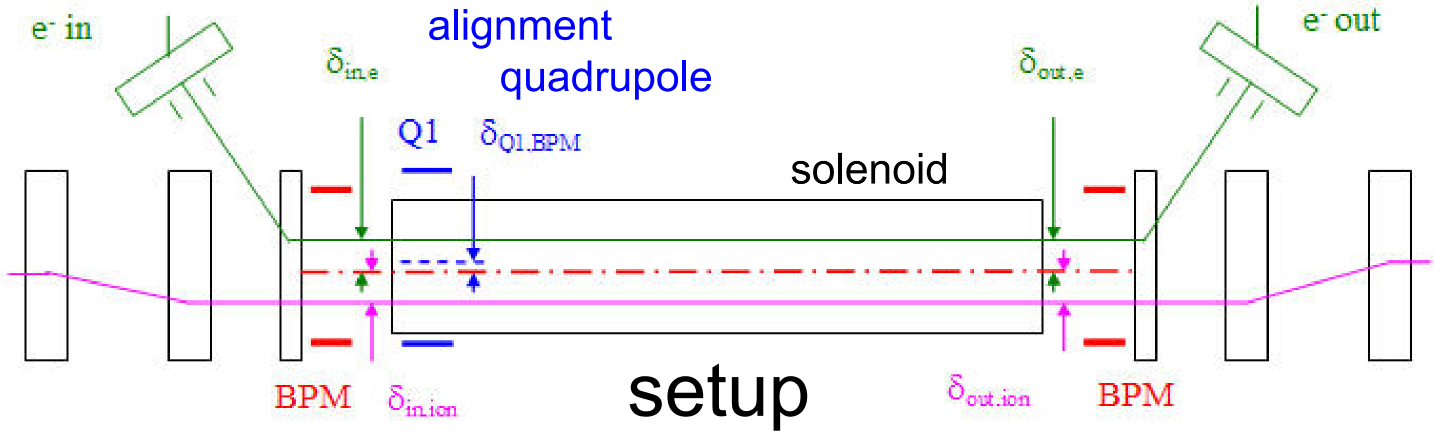
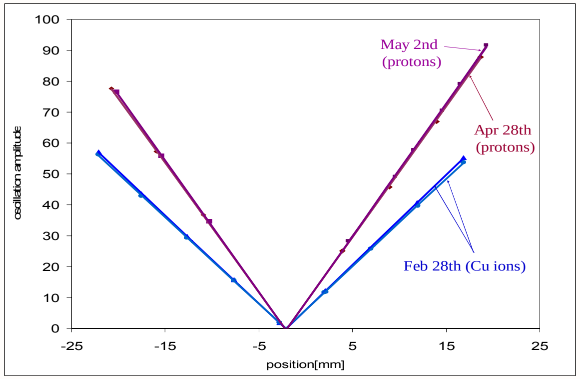
Beam-based Alignment



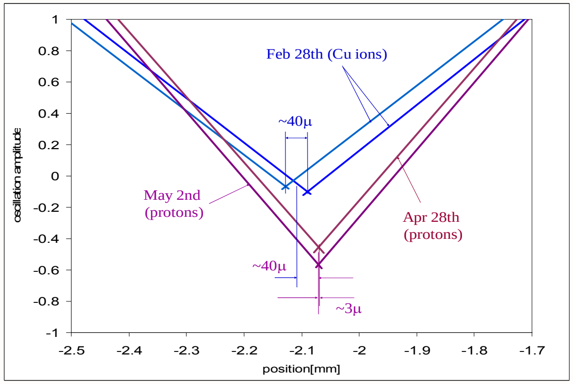
setup

measurement	accuracy	resolution	stability
$\delta_{Q1,BPM}$	7μ		
$\delta_{mod,ion}$	~125nm	~40nm	~40nm
$\delta_{in,ion}$ and $\delta_{out,ion}$	~3μ	~1μ	~1μ
$\delta_{Q1,e}$	7μ		
$\delta_{mod,e}$	~5μ	~2μ	~2μ
$\delta_{in,e}$	~3μ	~1μ	~1μ
$\delta_{t,e}$	~0.3μ	~0.1μ	~0.1μ

measurement requirements



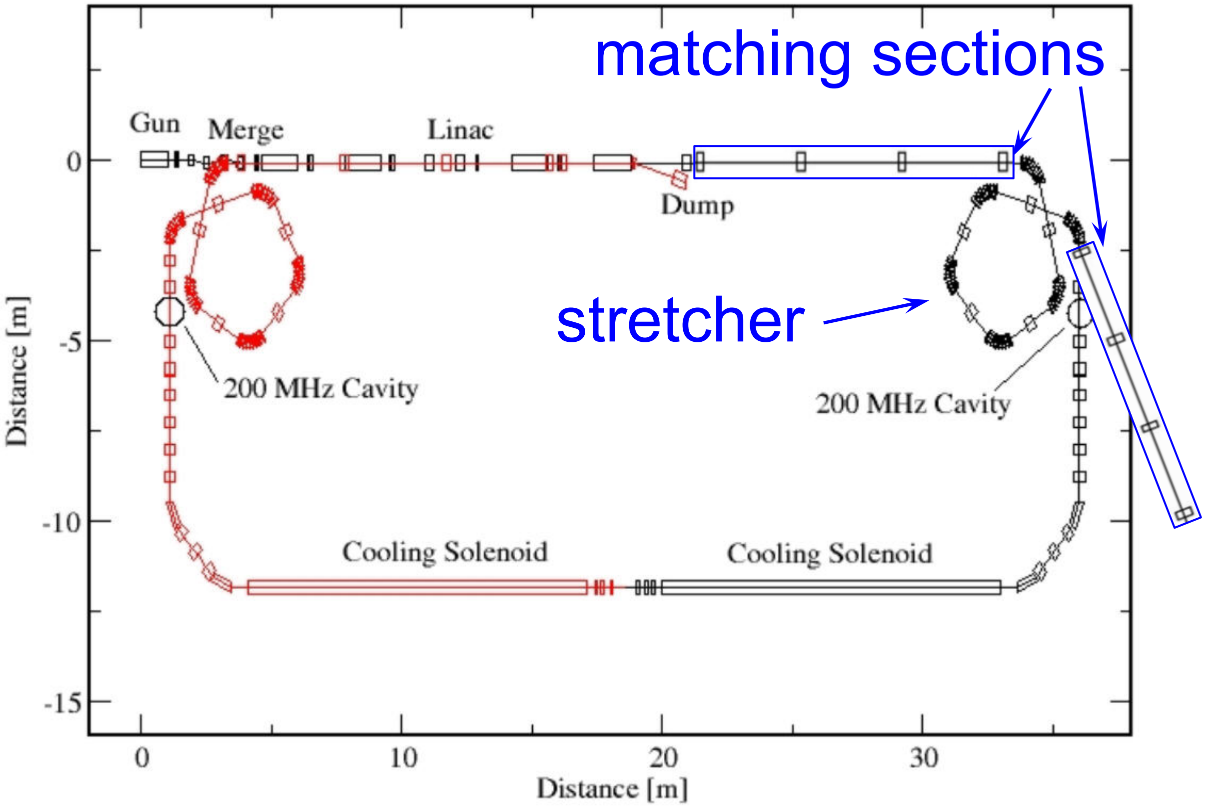
beam expt



zoom

P. Cameron et al, “BBA in the RHIC eCooling Solenoids”, PAC 2005

Magnetization Monitor



- Adjust betatron phase advances in matching section at end of linac to differ by 90 degrees in H and V - results in flat beam (**on flag**).
- From this extract the beam magnetization and the un-magnetized emittance.
- With diagnostic line/matching section downstream of the stretcher accomplish the same measurement
- This permits tuning of the dispersion and phase advance in the stretcher to minimize the contribution of longitudinal space charge to transverse emittance.

P. Cameron et al, "Beam Diagnostics for the RHIC eCooling Project", DIPAC 2005

Conclusions

- Move to non-Magnetized Cooling removes two major Diagnostics
  - BBA is potentially difficult
  - Magnetization monitor is straightforward, but requires dedicated matching line
- Move to two-pass ERL permits direct utilization of prototype ERL Diagnostics
  - Only 'new' Diagnostics for eCooling will be velocity matching, recombination monitor, and cooling section fast BPMs