Permanent Magnets for the ILC Damping Ring

BNL capabilities

BNL Capabilities

- Magnet design, simulation
- Construction of prototypes
- Magnet measurement (R&D and production)
  - BNL harmonic rotating coil with 10^{-5} repeatability
  - NSLS-II magnet diagnostics (vibrating wire etc.)
- Magnet tuning/shimming
  - Used in the production run of 216 permanent magnets for the CBETA multi-turn ERL

Magnet Parameters Outline

- Fields, gradients and apertures
- Field quality, good field region
- Field adjustability range and how often
- Field stability (temperature, vibration)
- Radiation resistance
- Cost envelope

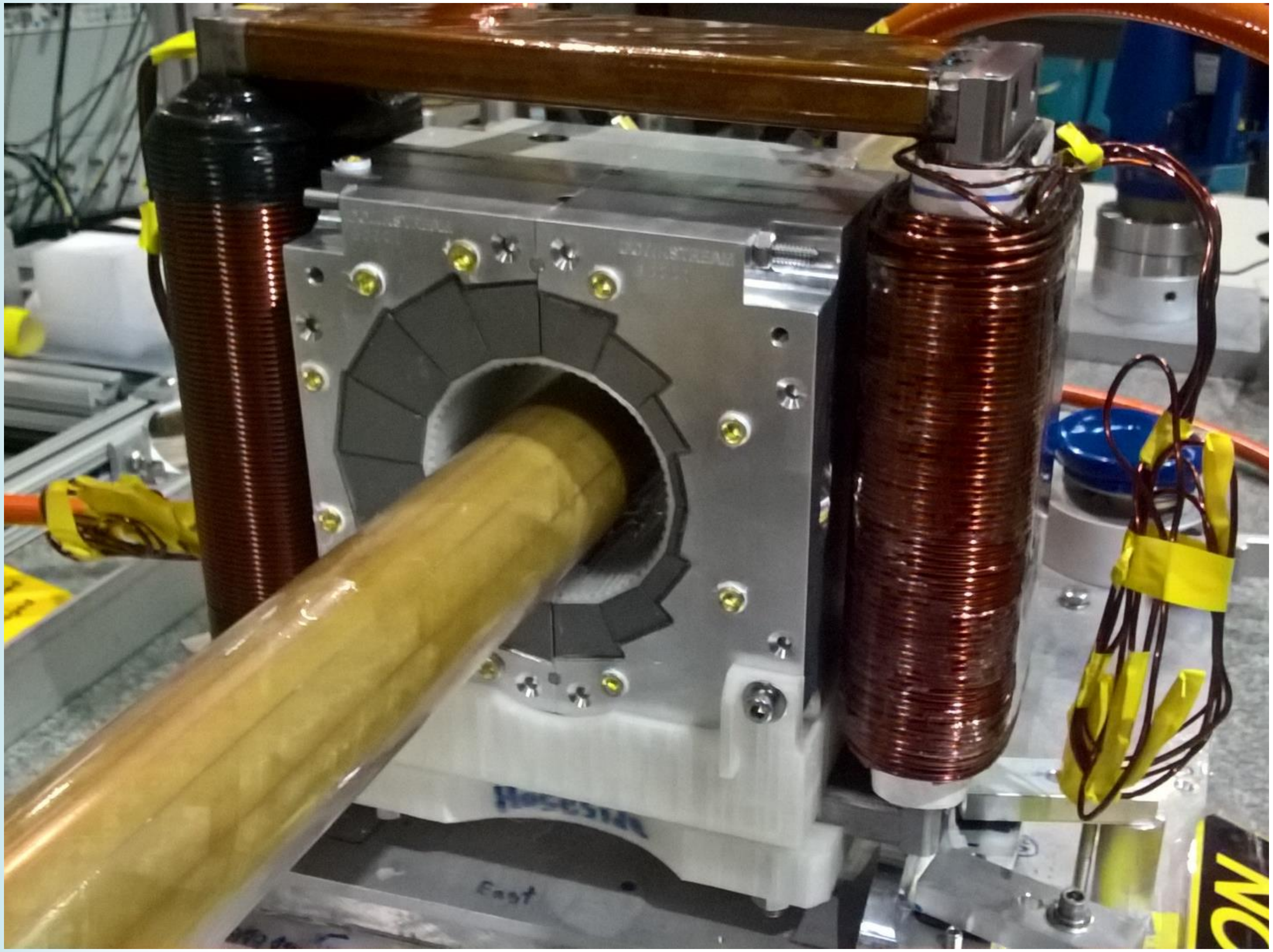
} (material grade)

Fields, Gradients and Apertures

Parameter	DR dipole	DR quad.	DR sext.	CBETA QF	CBETA BD
Dipole	0.14 T			0	-0.3081 T
Gradient		15 T/m		-11.562 T/m	11.147 T/m
Sextupole			75 T/m^2		
Aperture Ø	65mm	65mm	65mm	86.2mm	80.2mm
Length	5.0m	0.6m, 0.3m	0.3m	0.133m	0.122m
Number	150	450 + 213	600	107	32 + others

- Some similarity to CBETA magnet parameters
- Easy to make magnets longer (join segments)
- Mass production @ good quality already done

CBETA Permanent Magnets



Halbach design made of NdFeB material

This is a combined dipole+quad

Being measured on rotating coil at BNL

3D printed multipole corrector pack inside

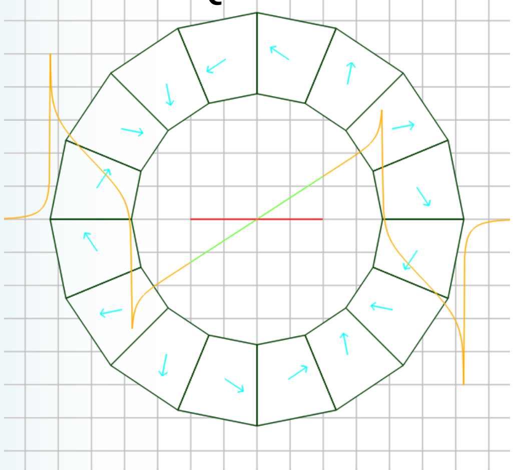
Windowframe corrector coil outside

Temperature stabilised by water (orange hoses)

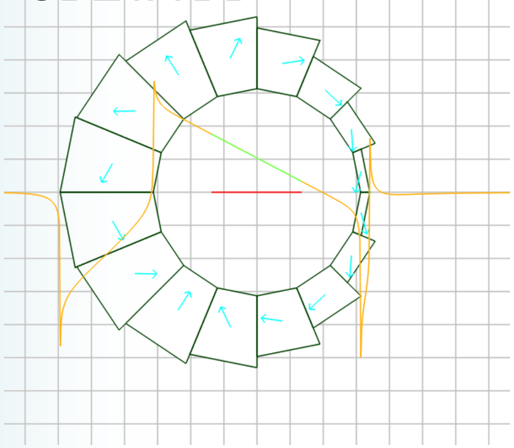
CBETA Fixed-Field Return Arc

Magnet Cross-Sections (to scale)

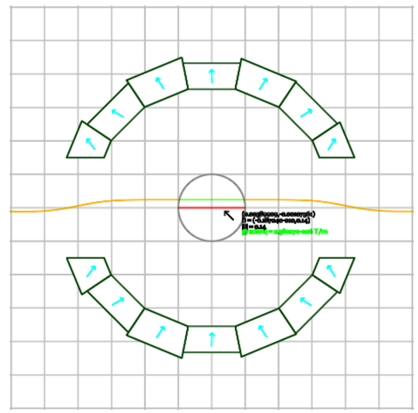
CBETA QF



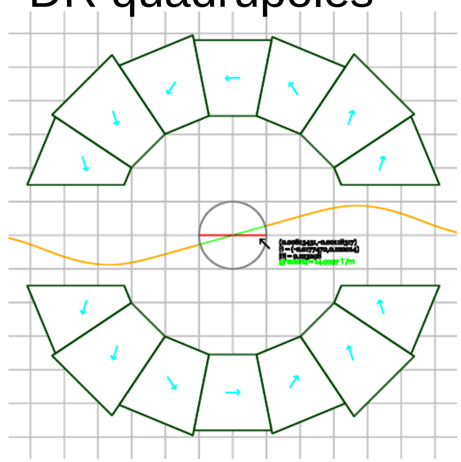
CBETA BD



DR dipole



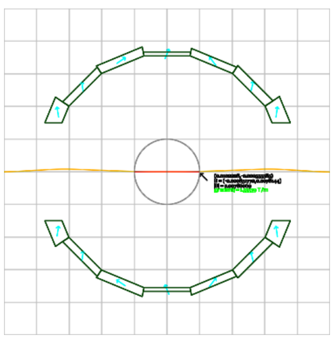
DR quadrupoles



Design rules:

- R=10mm good field
- $<5\times10^{-5}$ harmonic error
- 30mm gap for synchrotron radiation
- B_r=1.12T material (NdFeB high rad. tol.)
- B_r=1.158T for CBETA (NdFeB N35EH grade)

DR sextupole



- Could use SmCo with slightly larger area

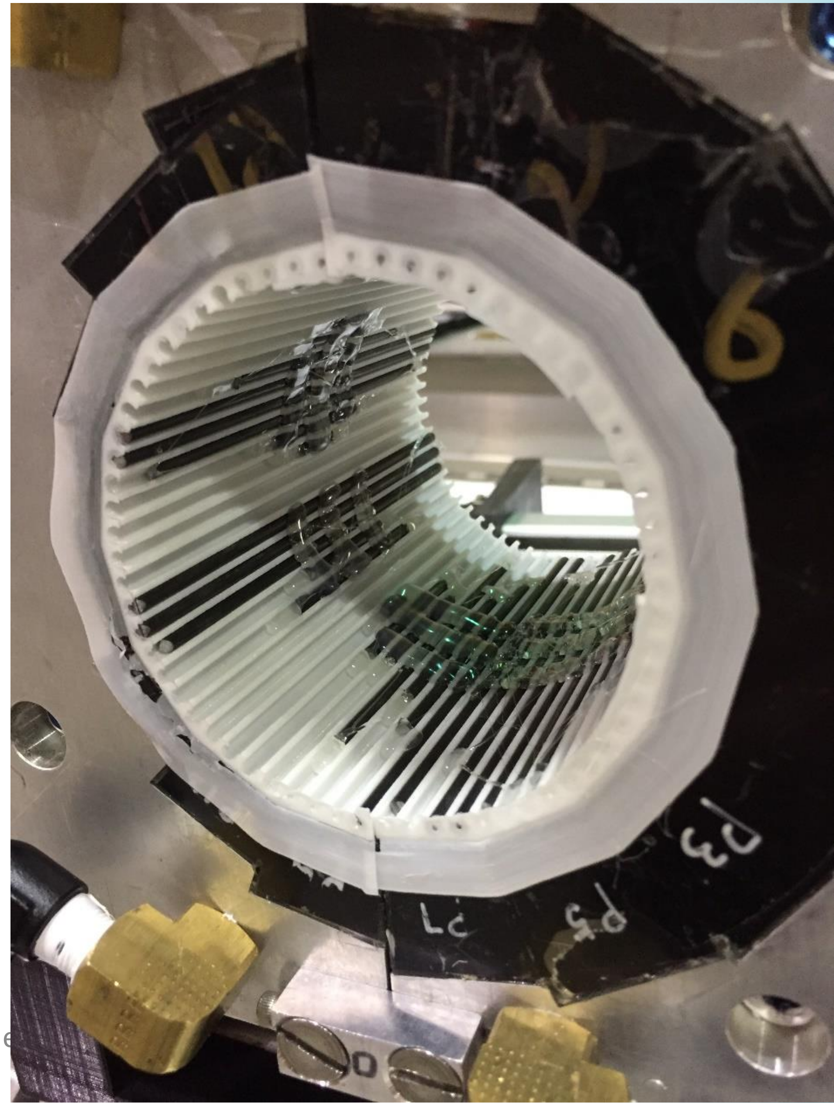
Field Quality, Good Field Region

- Field quality depends strongly on good field region radius definition (smaller R is easier)
- CBETA achieved $<10^{-3}$ on R=25mm (quite big)
  - Absolute strength $<5\times10^{-4}$

Relative field error	Initial	Tuned
Average	1.82×10^{-3}	2.19×10^{-4}
RMS	2.20×10^{-3}	2.56×10^{-4}
Maximum	9.81×10^{-3}	6.15×10^{-4}
Minimum	4.41×10^{-4}	3.05×10^{-5}
Median	1.50×10^{-3}	1.90×10^{-4}

Shimming/Tuning Methods

- Shimming/tuning methods are critical for permanent magnet field quality
  - CBETA inserted iron rods within the bore (~8× improv.)
    - 3D printed insert
    - Process can be automated
  - Other options:
    - Mechanically adjust (CESR IR)
    - Block sorting (B_r only)



Adjustability Requirements

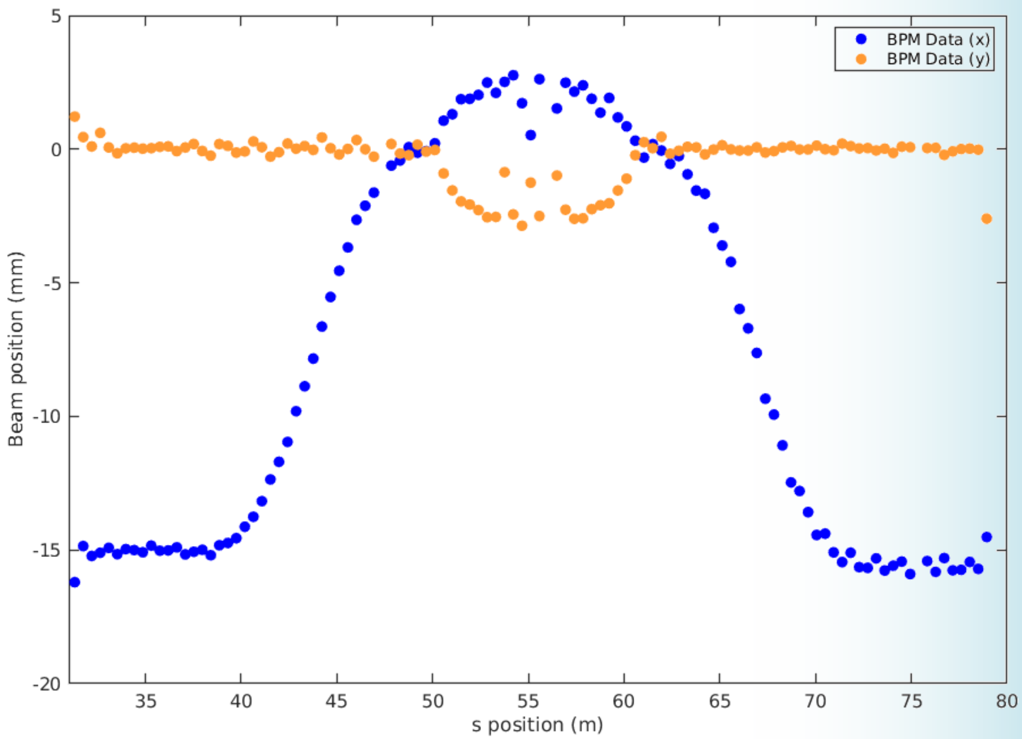
Magnet	Adjust Range	Adjust Frequency
Arc dipole	fine adjustment	During commissioning only
Arc quad.	30%	
Straight quad.	0-100%	
Arc sextupole	30%	

- CBETA's windowframe EM corrector gives a field change of 0.027 T at ~24W power
  - This is a 9% relative field correction = 2.5mm shift
- Other methods for larger but less frequent adjustments include mechanical, rotation etc.

CBETA Closed Orbit Bumps (1-turn)

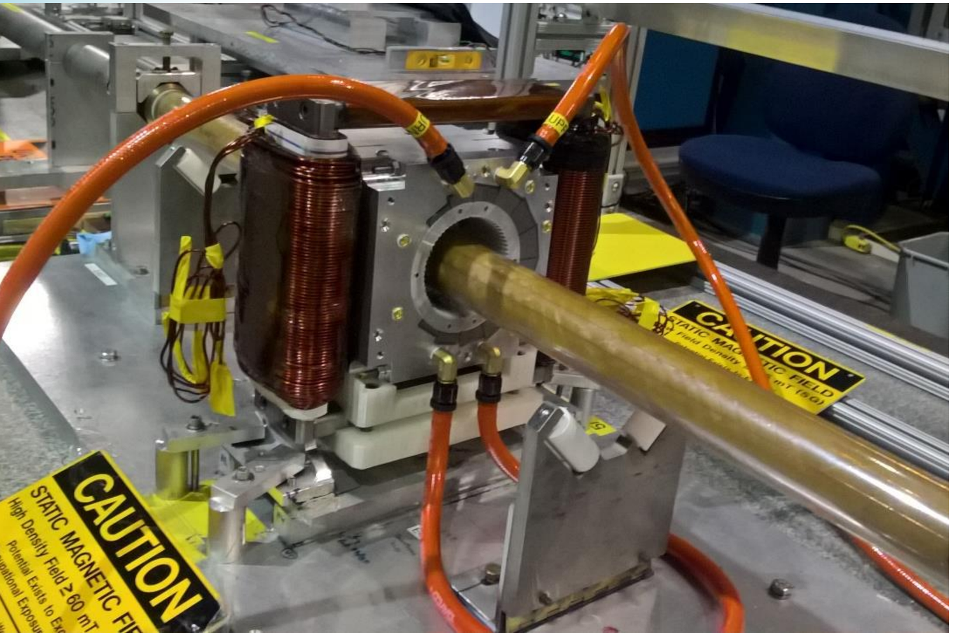
- Use of EM correctors on beam orbit

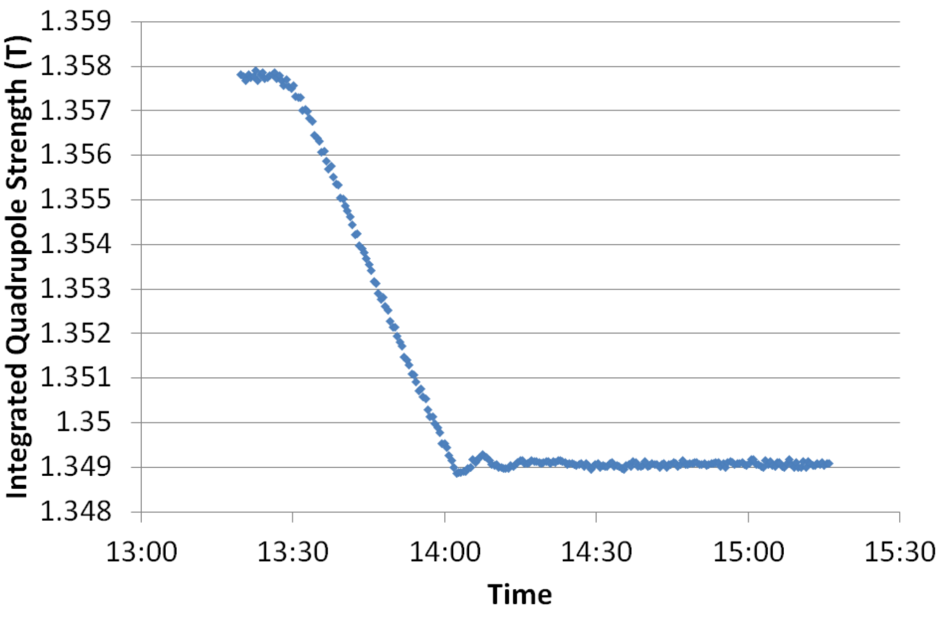
(November 6, 2019)



Stability (Temperature)

- NdFeB temperature coefficient is -1.1×10^{-3}
- Magnet housing contains water channels
  - Temperature stability better than ±0.2K
  - Strength variation less than 10^{-4}





Radiation Resistance

- Depends strongly on material coercivity grade
  - High field strength can also reduce resistance
- CBETA used NdFeB (N35EH) with 1kGy limit
  - Projected 74kGy = 1% field loss
  - Magnets instrumented with CsI dosimeters
- SmCo material is ~20% weaker field but ~100x more resistant to radiation
- See also A. Temnykh, NIM A **587**, 13 (2008)

Material Cost

- CBETA 27.3m length for $700k in PM material
  - DR 1264m for $33M material using length scaling
- By volume, $4.48/cm^3 for CBETA (incl. spares)
  - DR $15.6M, or $5.8M for just the arc dipoles
  - Price could go lower for larger orders

Parameter	DR dipole	DR quad.	DR sext.	CBETA QF	CBETA BDx
Length	5.0m	0.6m, 0.3m	0.3m	0.133m	0.122m
Number	150	450 + 213	600	107	107
Total length	750m	333.9m	180m **Σ=1264**	14.2m	13.1m **Σ=27.3**
Area	17.3cm^2	62.9cm^2	4.72cm^2	50.9cm^2	65.3cm^2
Volume/cm^3	8665	3776, 1888	141	676	797
Total vol./m^3	1.30	2.10	0.085 **Σ=3.49**	0.072	0.085 **Σ=0.158**

Recommendations

- Looks like a CBETA-derived design could be a good fit for the ILC DR arc dipoles
  - Other magnets require more adjustment
- Building and measuring a prototype at BNL is comparatively easy
  - A few person-months effort, maybe $20k material
- Should try to define other issues
  - Radiation levels in the tunnel environment
  - Required field quality, **size of good field region**