Septa considered for the FCC-hh beam dump system

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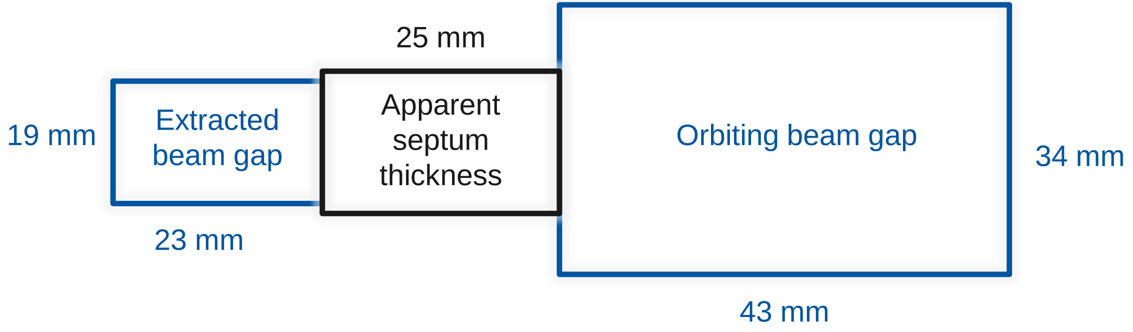
Outline

- FCC beam dump requirements
- Lambertson limitations
- Pacman as a massless septum solution
  - Comparison with previously reported massless septa
- Double Pacman
- Stealth dipole proposal and massless variant
- Truncated cosine theta
- Conclusions

FCC gap and septum blade dimensions

Assuming injection at 3.3 TeV.
Extraction septa dimensions.

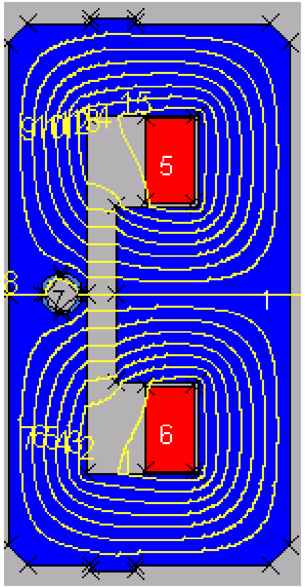


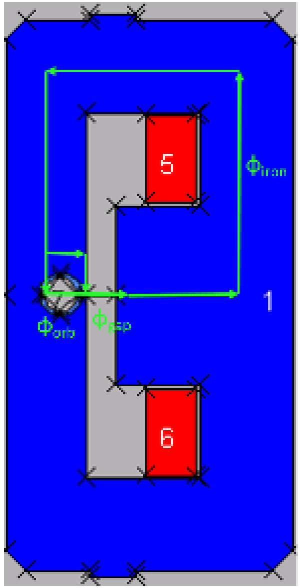
Parameter	Unit	Value
Available length	m	120
Magnetic field integral	Tm	190
Total deflection	mrad	1.15
Blade thickness	mm	25
Good field region (hor/ver)	mm	19
Leak field integral	mTm	924
Total dump line length	km	2.8

See talk by F. Burkart

Picture to scale

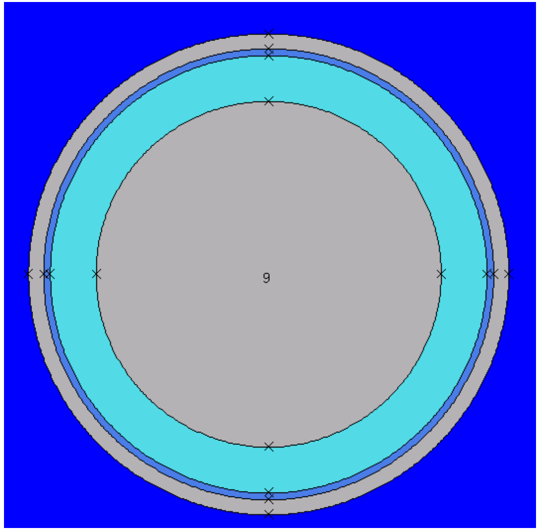
LHC Lambertson septa limits





0.9 mm sheet of Mumetal around the vacuum chamber (7 mm thick in total)

The maximum field reachable is 1.36 T with a 25 mm apparent septum thickness while respecting the leak field requirements



Scaled LHC solution using Lambertson septa

Parameter	Unit	Unique type
Magnetic field integral	Tm	190
Nominal magnetic field	T	1.39
Number of magnets per extraction line	-	35
Apparent septum thickness	mm	25
Total current (NI)	A·turns	56832
Current	A	1184
Coil turns	-	48
Power consumption per magnet	kW	62
Total power consumption (1 dump line)	kW	2155
Total power consumption	kW	4311

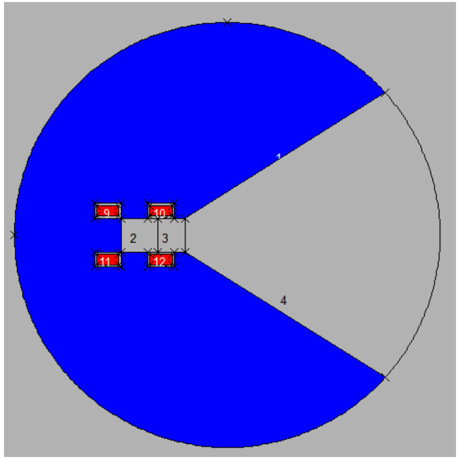
Parameter	Unit	FCCA	FCCB	FCCC
Magnetic field integral	Tm	56	60	75
Nominal magnetic field	T	1.39	1.49	1.57
Number of magnets per extraction line	-	10	10	12
Apparent septum thickness	mm	25	31	37
Total current (NI)	A·turns	56832	66304	75776
Current	A	1184	1184	1184
Coil turns	-	48	56	64
Power consumption per magnet	kW	62	72	77
Total power consumption (1 dump line)	kW	616	718	924
Total power consumption	kW	4516		

Power consumption comparable,

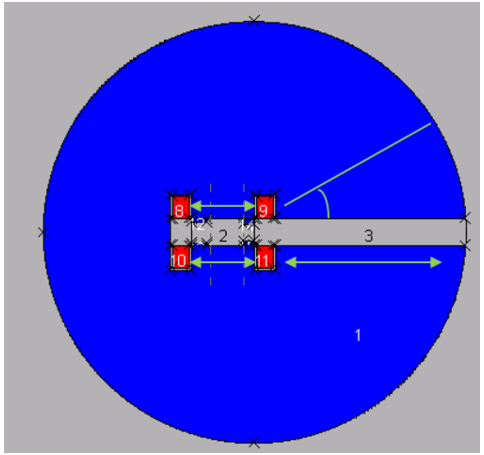
Using three types the number of magnets, and the total length decreases from 35 to 32 units and from 137 to 128 m.

Introducing the Pacman septum (massless)

Pacman concept



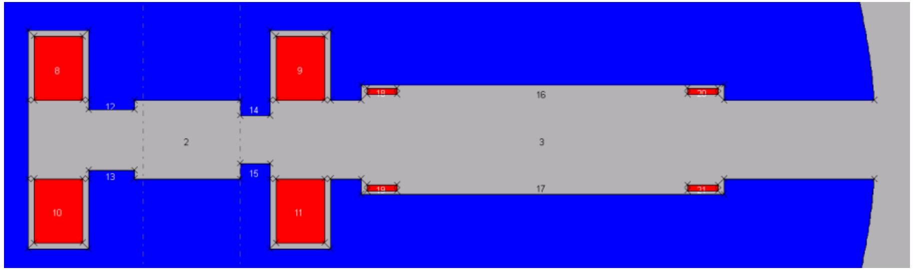
Optimized cross-section



- Geometry optimization, compensation coils and shimming
- Can be massless or close the yoke (shunt the magnetic circuit around both beams)

Optimised massless Pacman septum

- Apparent septum thickness ≈ 1.8 x h (h = gap height) i.e. 34 instead of required to 25 mm. Low sensitivity to field level.
- B < 2 T and Leak field ≈ $5 \cdot 10^{-3}$ T
- Closing the gap reduces the leak field level, not the transition region width.
- Can be built either super ferric or normal conducting.

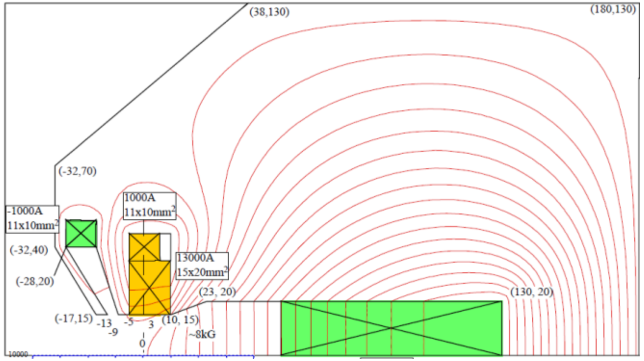


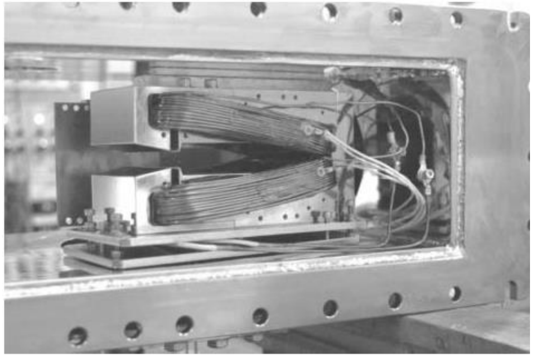
Optimised to achieve:
$B_0 = 1.8$ T
$B_{leak} = 5 \cdot 10^{-3}$ T
Resulting septum width (1 – 99%): 34 mm

Previously reported massless septa

Iwashita
(Simulations)

[1]





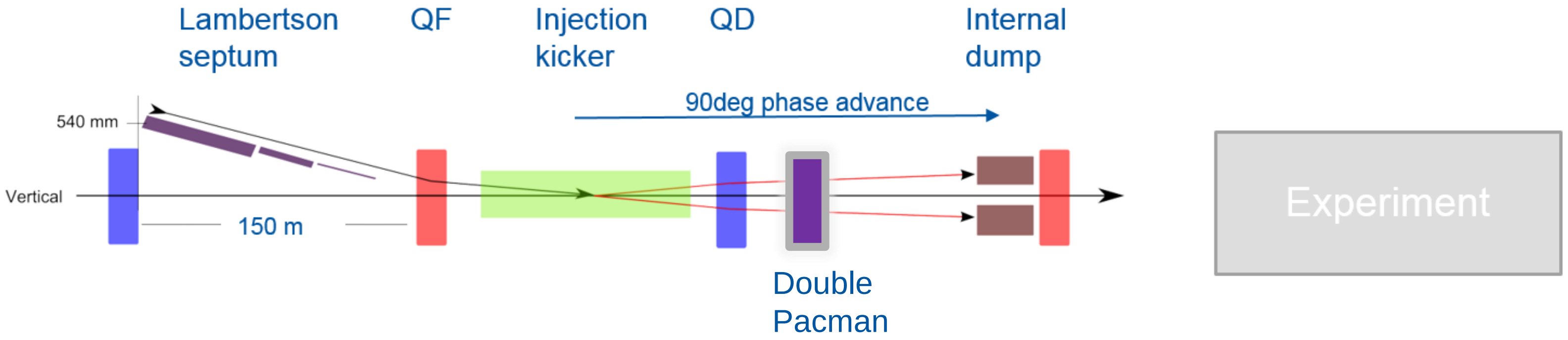
Yonemura
(built)

[2]

	Unit	Pacman	Iwashita	Yonemura
Magnetic field	T	1.8	0.8	0.1
Leak field	mT	8	<1	<1
Apparent septum thickness	mm	35	40	33
Gap height	mm	19	30	20
Apparent septum thickness/ Gap height	-	1.8	1.3	~1.6

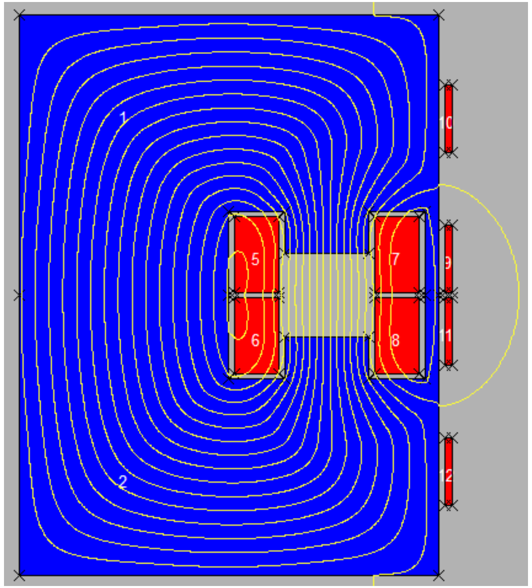
Converge to Pacman geometry if pushed to high fields (2 T)

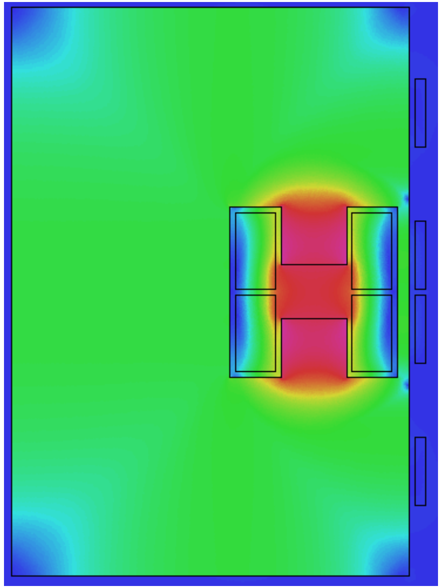
Double Pacman



- Use a massless opposite fields septum to kick a mis-injected beam into a TDI. More suitable for injection since the energy is constant. QD still necessary.
- Same function as a defocusing quadrupole but with a zero field region at the centre instead of a point. No impact on the optics of mis-steered beam.
- Preliminary values: 1m long, 0.65 T. To confirm with collimation team if this is of interest.

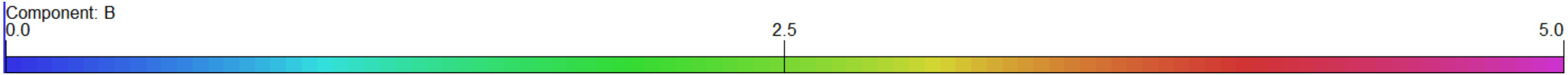
Stealth dipole proposal



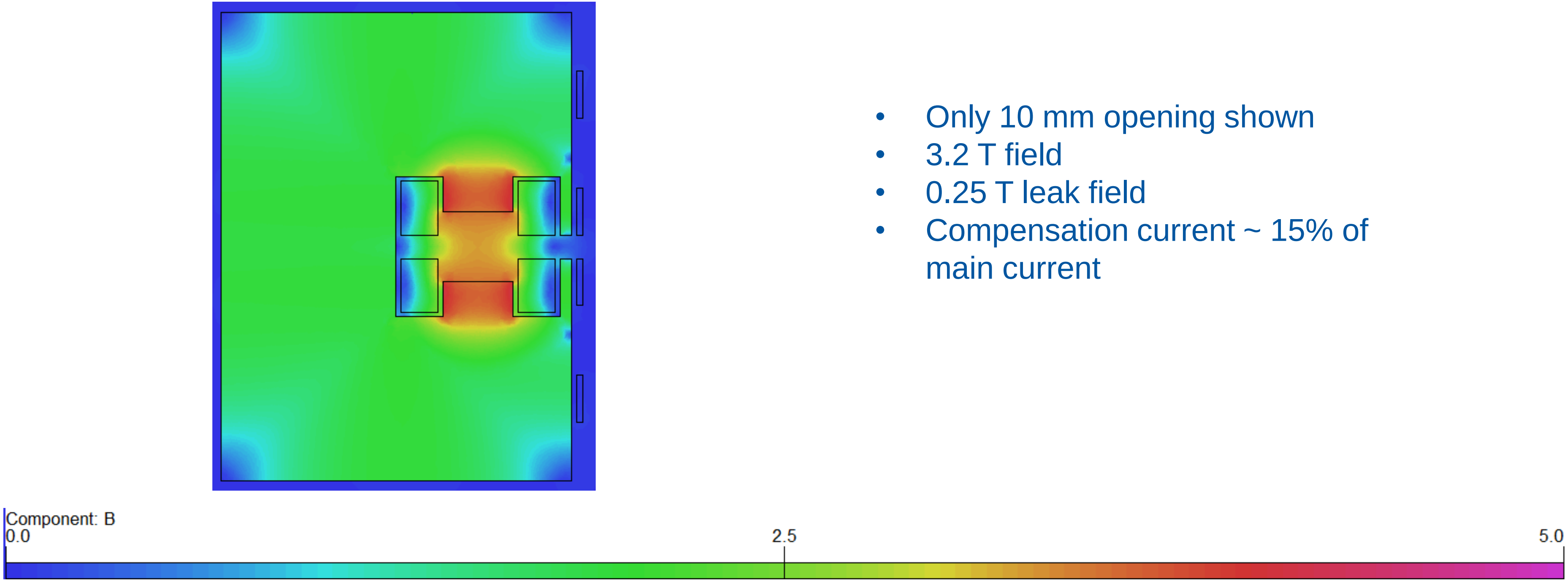


Texas A&M (Peter McIntyre and Akhdiyor Sattarov)

- 4 T field
- 0.1 T leak field
- 25 mm apparent septum thickness
- Compensation current ~ 2% of main current
- Designed for cable in conduit
- B vs. I not linear



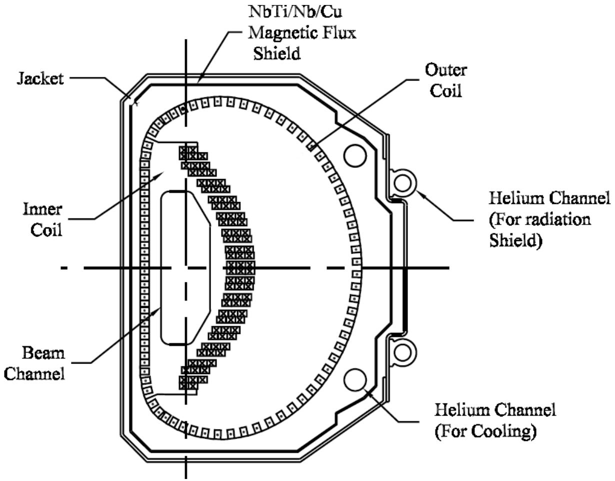
Massless variant of Stealth Dipole

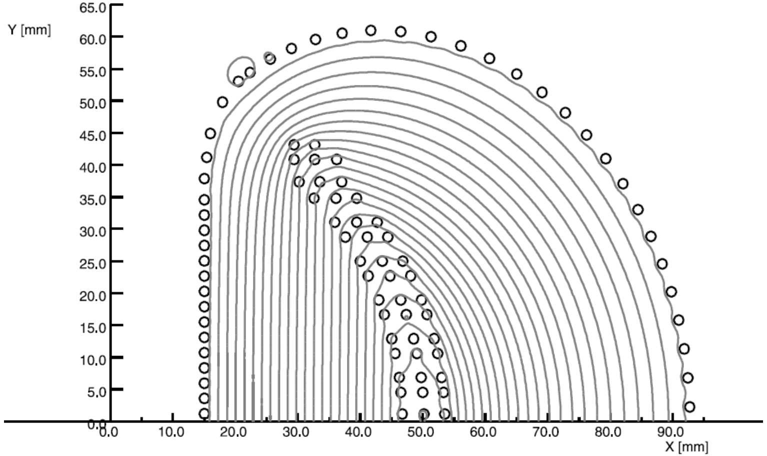


- Only 10 mm opening shown
- 3.2 T field
- 0.25 T leak field
- Compensation current ~ 15% of main current

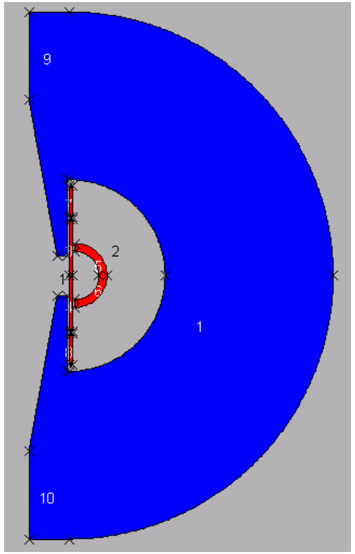
g^{-2} double truncated cosine theta

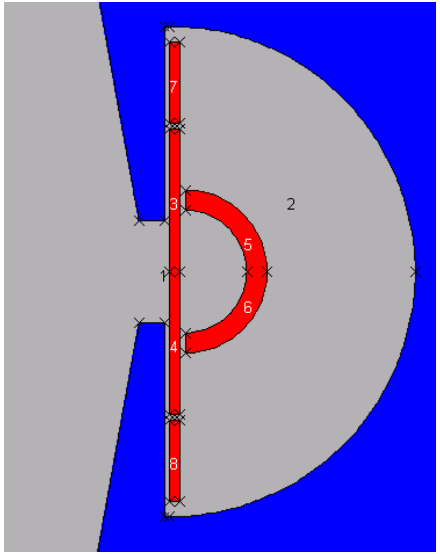
Double truncated cosine-theta built for g^{-2} experiment [3].





Modified Truncated Cosine Theta



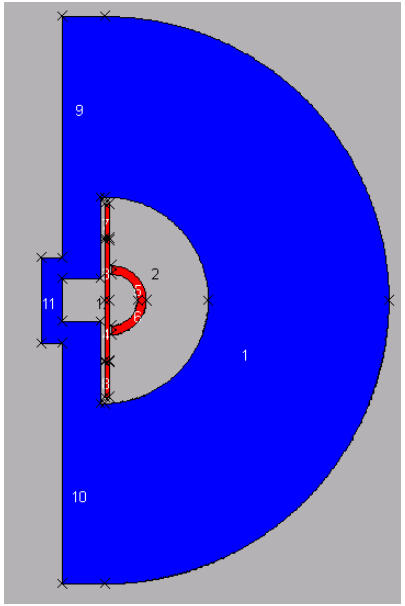


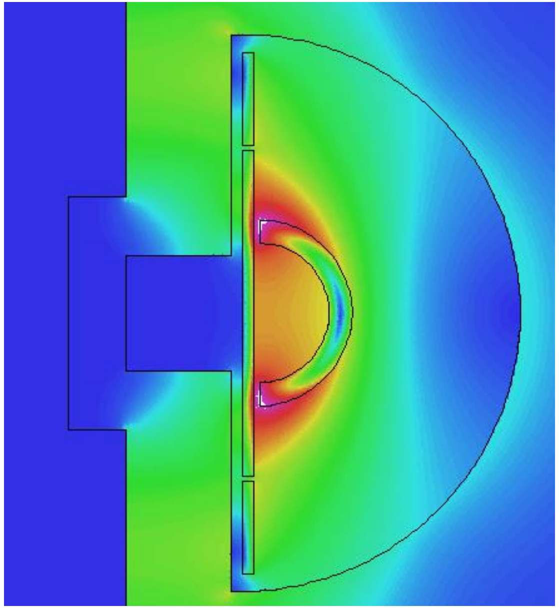
GSI proposal 2016

- Linear relationship B vs. I
- Promising outlook:
  - Cable type under study,
  - Challenging 3 D design (coil head),
  - Stress levels within acceptable limits.

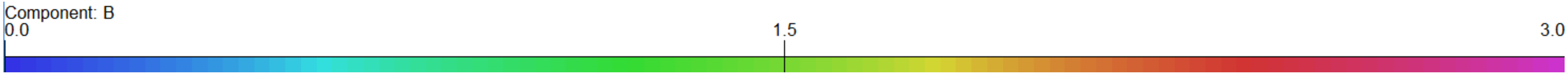
See [4] and Kei Sugita's talk: Design status for a high field superconducting septum magnet

Shielded GSI design



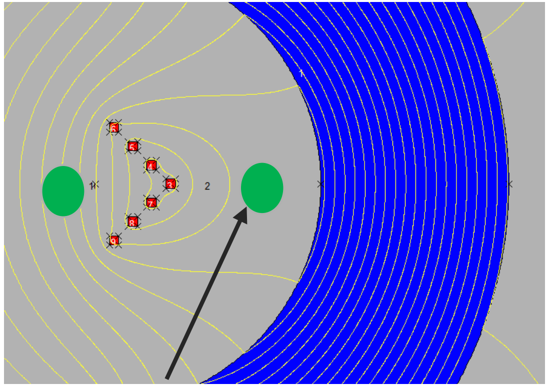


Leak field can be reduced by shunting the magnetic circuit around the two beams (< 20 mT).

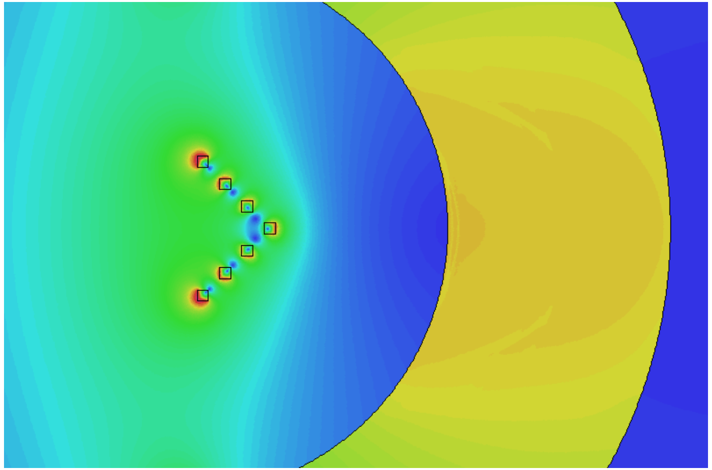


Super conducting geometry

Super ferric magnet obtained using algorithm that determined location of conductors as a function of the required field profile. (Useful as a first iteration [5, 6])



Orbiting beam gap

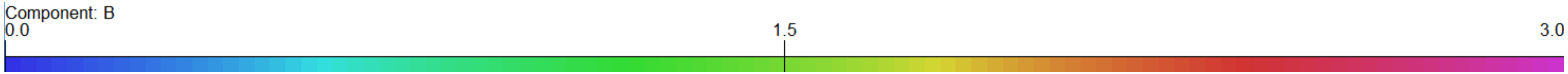


Unipolar configuration

- Can it act as a massless septum?
- Close the coil outside the yoke (not shown)

Bipolar configuration

- Same case as in previous slides



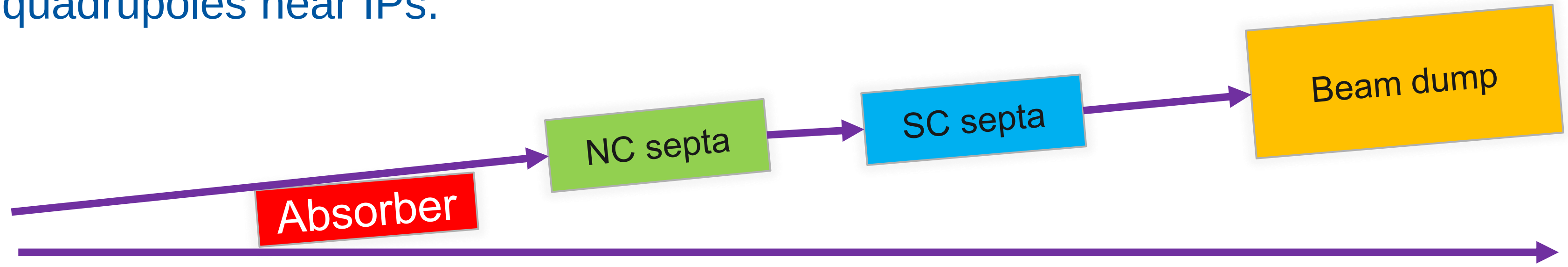
Septa alternatives

FCC extraction assumptions 1.15 mrad and 190 Tm											
		Field (T)	Leak field (mT)	Apparent septum thickness (mm)	Magnetic length (m)/ Field leak integral (Tm)	Extracted beam gap (mm)	Orbiting beam gap	Power (kW)	protection needed	Number of planes	Limiting factor
SuShi*		2.6	<0.1	<25		45		cryo	Yes	1	Quench, Bmax, Delta T
Pacman-SF		1.5	<5	34 (1.8 gap heights)	~127 (190 Tm)	19x23	34x43	cryo	Yes	1	Gap height-> leak field
Truncated cos theta		1.8	< 20	< 1 gap height	100 (190 Tm)	120	34x43	cryo	Yes	1	Stress, cable
Lambertson	NC	1.39	<5	25	14.28 (20 Tm)	32	150 x 45	62	No, robust	2	Air+mumetal
Lambertson	SF	1.39	<5	25	~134 (166 Tm)	32	150 x 45	cryo	Yes	2	Air+mumetal

*See talk by D. Barna "First experimental results with the superconducting shield septum prototypes" and [7].

Conclusions

- Beam dump septa system is feasible with various alternatives
- Even if using a massless variant, beam impact on the septum, or absorber is still to be studied for the CDR.
- For SC septa, it is necessary to use a staged approach: first normal conducting (for robustness), followed by Super conducting septa (showers can quench this septum, even with absorbers). This strategy is presently used in LHC with warm quadrupoles near IPs.



Thank you

References

[1] I. Iwashita et al. Massless septum with hybrid magnet. EPAC 98, Luzern.
[2] Y. Yonemura et al. Beam extraction of the pop ag with a massless septum. Proceedings of the PAC 2003.
[3] A. Yamamoto et al. The superconducting inflector for the BNL g^{-2} experiment. Nuclear Instruments and Methods in Physics Research A 491 (2002)
[4] K. Sugita et al. Basic design aspects for superconducting high field septa. Submitted to PRAB special issue FCC Week 2016
[5] S. Fartoukh. A semi-analytical method to generate an arbitrary 2D magnetic field and determine the associated current distribution. LHC project report 1012, 2007.
[6] A. Sanz Ull. Note on the application of fartoukh's algorithm. TE-ABT Internal note, 2016
[7] D. Barna. High field septum magnet using a superconducting shield for the Future Circular Collider. PRAB April 2017. https://link.aps.org/doi/10.1103/PhysRevAccelBeams.20.041002

Backup. Leak field calculation

$$B\rho_{LHC} = 11e3\ and\ 1501\ at\ extraction\ and\ injection\ \text{(TDR)}$$

$$B\rho_{FCC} = 166Tkm \cdot \frac{3.3TeV}{50TeV} = 11Tkm$$

From LHC Lambertson: Bleak= 2.1 mT (I take it as a homogeneus leak value. It's very conservative). 15 MSD, 4 m long each (magnetic)

$$\int B_{leakLHC} = 2.1\ mT \cdot 15magnets \cdot 4m/magnet = 126mT \cdot m$$

Now we scale that leak field with the beam rigidities to obtain the TOTAL leak field allowed for FCC dump septa

$$\int B_{leakFCC} = 126mT \cdot m \cdot \frac{11e3\ T \cdot m}{1501\ T \cdot m} = 924\ mT \cdot m$$

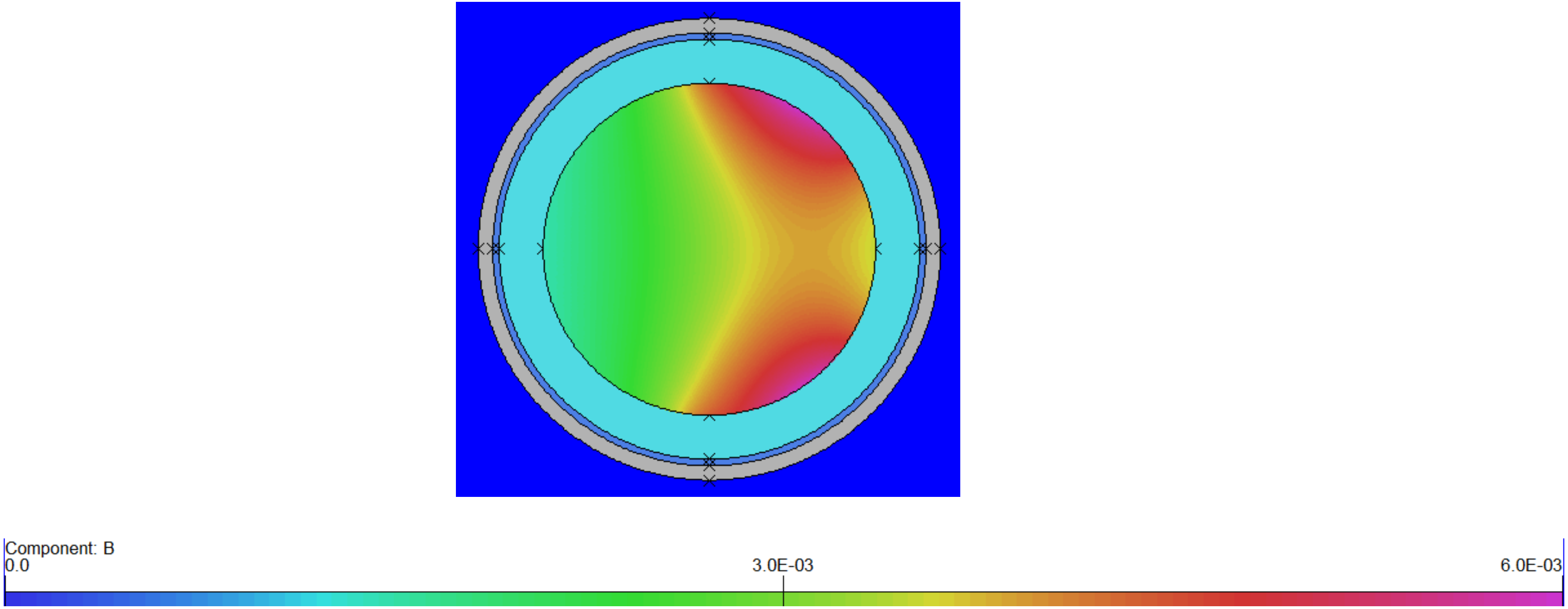
And this leak field, since it's integrated, we do the inverse sequence as before. Divide it by N magnets, Y m long each (35 magnets, 4 m for FCC Lambertsons=6.6 mT)

Backup. Full table Lambertsons

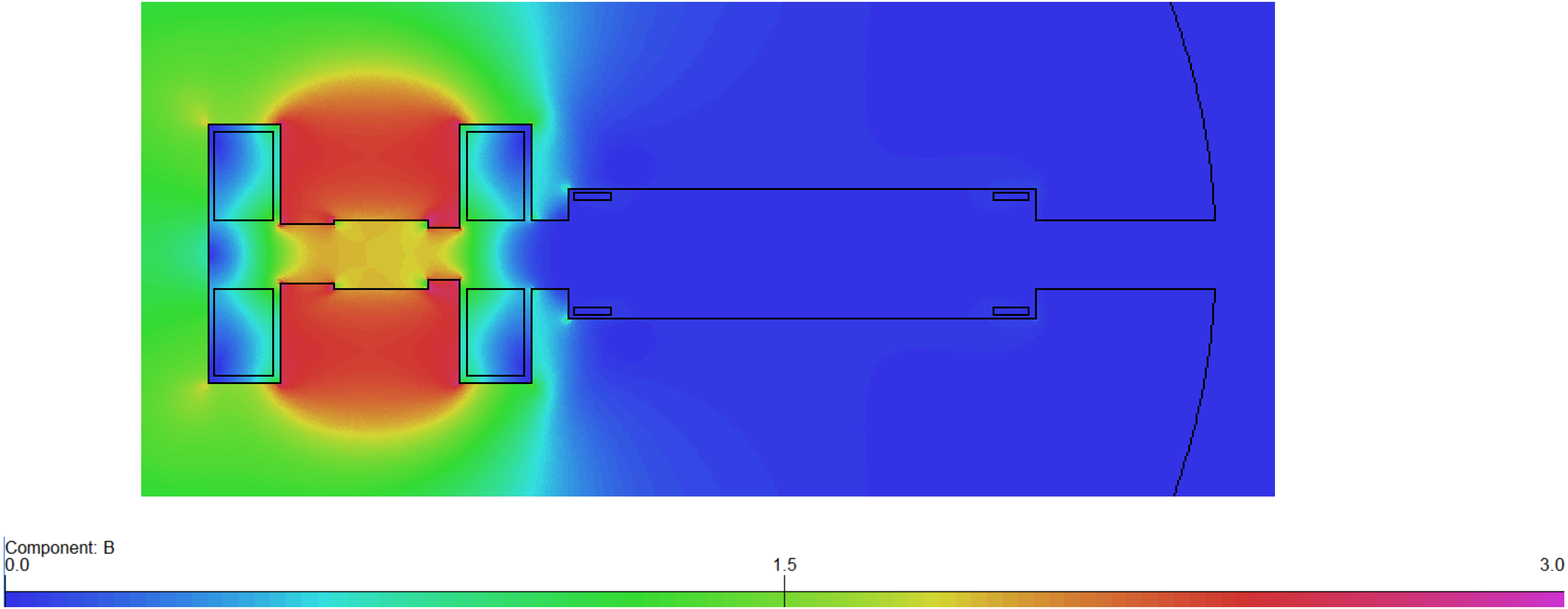
Parameter	Unit	Unique type
Magnetic field integral	Tm	190.00
Nominal magnetic field	T	1.39
Magnetic length	m	139.70
Magnet line fill factor	%	85
Physical length	m	164.36
Mass per magnet (estimated)	tons	9.25
Individual magnet length	m	4.46
Number of magnets per extraction line	-	35
Apparent septum thickness	mm	25
Total current (NI)	A·turns	56832
Current	A	1184
Coil turns	-	48
Power consumption per magnet	kW	62
Total power consumption (1 dump line)	kW	2155
Total power consumption	kW	4311

Parameter	Unit	Type A	Type B	Type C
Magnetic field integral	Tm	55.6	59.6	75.36
Nominal magnetic field	T	1.39	1.49	1.57
Magnetic length	m	40	40	48
Magnet line fill factor	%	0.9	0.9	0.9
Physical length	m	4.46	4.46	4.46
Mass per magnet (estimated)	tons	9.25	9.25	9.25
Individual magnet length	m	4	4	4
Number of magnets per extraction line	-	10	10	12
Apparent septum thickness	mm	25	31	37
Total current (NI)	A·turns	52475	61221	65593
Current	A	1093	1275	1367
Coil turns	-	48	48	48
Power consumption per magnet	kW	62	84	96
Total power consumption (1 dump line)	kW	616	838	1155
Total power consumption	kW	5217		

Backup. Lambertson leak field map



Backup. Pacman leak field map



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