MCTF ACTIVITES

Andreas Jansson

“ If you can’t decide which new projects or ideas to bet on based on their objective merits, pick those that will be developed by the most committed and persuasive heretics “

from “The weird rules of creativity” by Robert I. Sutton
Harvard Business Review, 2001

Charge

The Committee is asked to review the activities of the MCTF and NFMCC activities at Fermilab, and offer comments on the strategic approach, the appropriateness of program goals (including with respect to timing), and the technical progress towards achieving these goals. The committee should note that the national Muon program will have been reviewed by the Muon Technical Advisory Committee four weeks before the AAC meeting. As such the AAC is specifically asked to **concentrate on Fermilab's contributions to these programs**. In formulating its comments and recommendations the committee should consider, and offer advice as appropriate, on the interaction between these activities and the broader national and international muon programs.

Overview of MCTF activites

- Collider scenario
- Collider ring design
- RF & power consumption
- Cooling channels
  - RFOFO snake
  - Helical Cooling Channel
- High Pressure RF test / MTA beamline
- HTS / High field solenoids

Collider Scenarios

Y. Alexahin

	Low Emit.	High Emit.	MCTF07
√s (TeV)		1.5	
Av. Luminosity (10^{34}/cm^2/s) *	2.7	1	1.33-2
Av. Bending field (T)	10	6	6
Mean radius (m)	361.4	500	500
No. of IPs	4	2	2
Proton Driver Rep Rate (Hz)	65	13	40-60
Beam-beam parameter/IP	0.052	0.087	0.1
β* (cm)	0.5	1	1
Bunch length (cm)	0.5	1	1
No. bunches / beam	10	1	1
No. muons/bunch (10^{11})	1	20	11.3
Norm. Trans. Emit. (μm)	2.1	25	12.3
Energy spread (%)	1	0.1	0.2
Norm. long. Emit. (m)	0.35	0.07	0.14
Total RF voltage (GV) at 800MHz	$407\times10^3\alpha_c$	0.21**	0.84**
Muon survival Nμ/Nμ0	0.31	0.07	0.2
μ+ in collision / proton	0.047	0.01	0.03
8 GeV proton beam power	3.62***	3.2	1.9-2.8

*) Luminosity calculated taking account of the hour-glass factor but ignoring the dynamic beta effect.
**) Momentum compaction in the present ring design $\alpha_c=1.5\times10^{-4}$. Note that it would be better to assume f=1.3GHz to keep the RF voltage at a reasonable level (0.52GV for MCTF07 set)
***) Assumes μ /p ratio of 0.15 after capture and precooling, and only decay losses afterwards. Positive and negative muons are assumed to be produced independently (from different protons).

Proton driver

- An upgraded Project X linac looks very attractive as MC proton driver
  - 8GeV high rep rate or
  - Acceleration to ~50GeV in MI
- Started looking into the specific upgrades that would be required
  - Feedback to Project X design team

C.Ankenbrandt *et al*

Collider ring design issues

Large β at strong quadrupoles (consequence of the extremely small β^*):

- large chromatic effects $\longrightarrow$ strong sextupoles $\longrightarrow$ reduced DA
- sensitivity to misalignments and field errors

"Advantage" (wrt. hadron machines): long term stability is not required !

Goal is an optics design fullfilling required

- luminosity (Small circumference, low beta*)
- energy acceptance
- DA
- very small $|\alpha_p|$

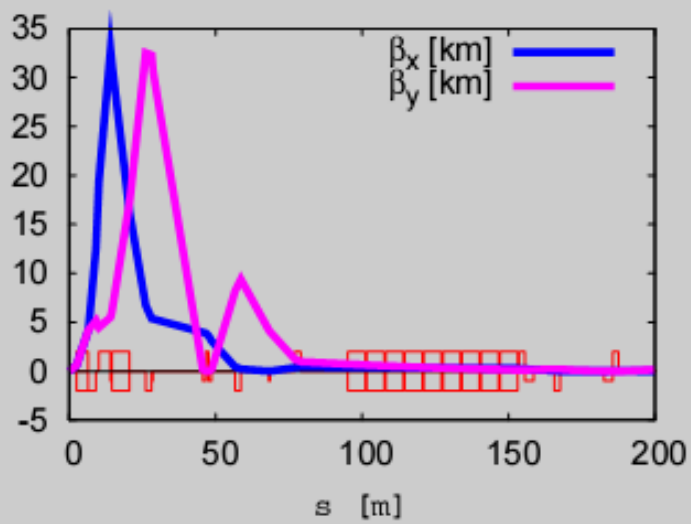
The design must be robust enough against

- misalignments and field errors

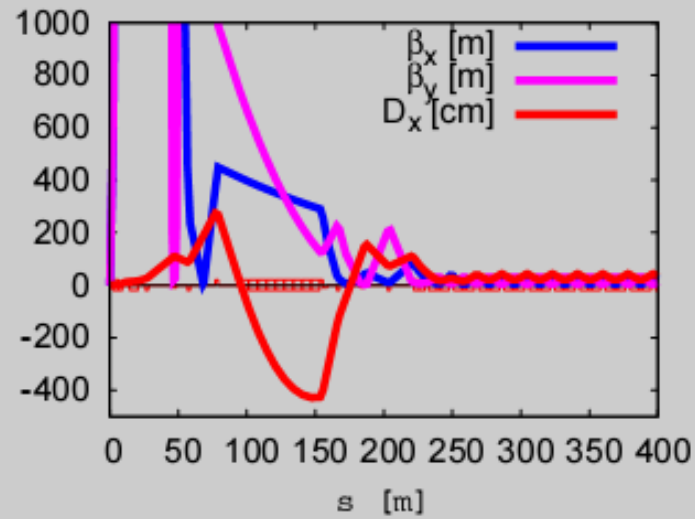
Y. Alexahin
E. Gianfelice-Wendt

“Dipole First” optics

Introduce a dipole (B=7.5 T, ℓ=4 m) before the first quadrupole to increase the dispersion at the IR sextupoles. Free space: $\pm$ 2.5 m



IR



Matching section

4 sextupoles located at 15, 29, 47 and 69 m correct the chromatic beta.

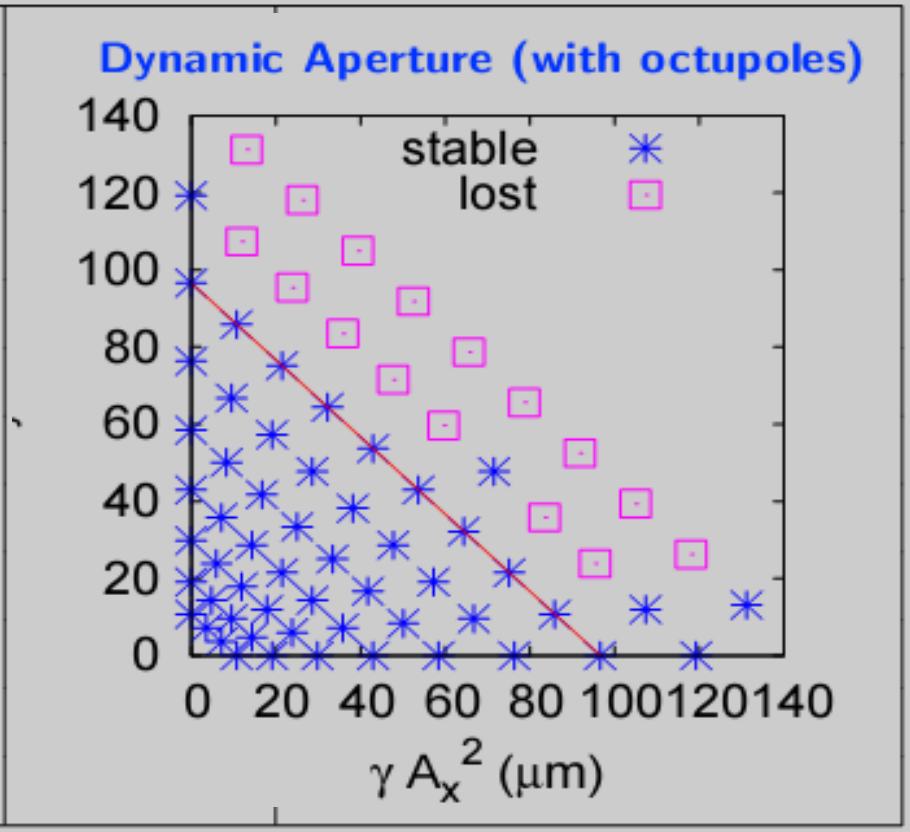
2 sextupoles at 158 and 185 m correct the 2th order dispersion.

Octupoles are located at 10, 21 and 26 m (detuning correction) and 154 m (2th order chromaticity).

Y. Alexahin
E. Gianfelice-Wendt

Recent design studies results

Energy (GeV)	Dipole First
L (m)	3132
B_{dip} (T)	9.6
Tunes	42.11/41.18
β^* (mm)	10
$\hat{\beta}$ (km)	33
# of IPs	2
distance to first quad (m)	$\pm$6 (2.5)
DA (# of σ)	2.8
momentum aperture	$\pm$ 0.6 %
α_p	-1.3$\times 10^{-4}$
length of RF sections (m)	-



Work ongoing….

Y. Alexahin
E. Gianfelice-Wendt

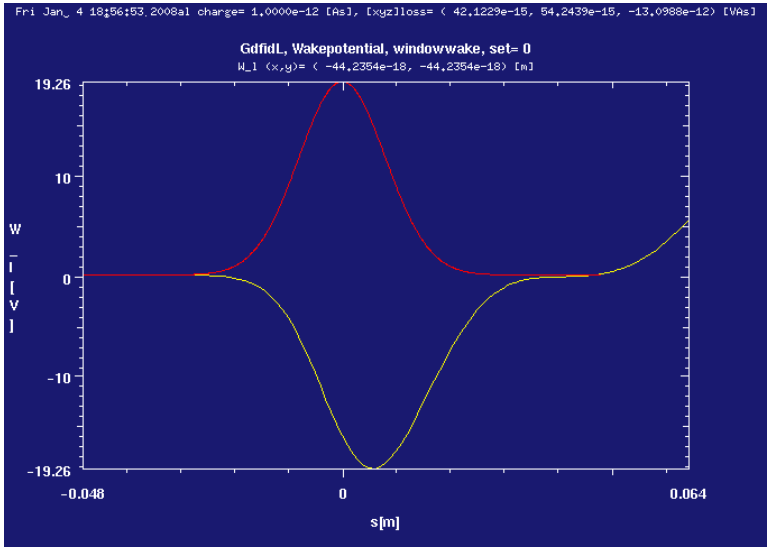
RF issues

Feature of the muon collider linac :
high bunch population, 1 $2\cdot10^{12}$

ILC linac – $2\cdot10^{10}$.

Problems:

1. Strong cavity loading by a single bunch;
2. Energy spread in the bunch;
3. Bunch timing;
4. Transverse kick and emittance dilution.
5. RF – kick
6. Muon decay electrons (heat load)

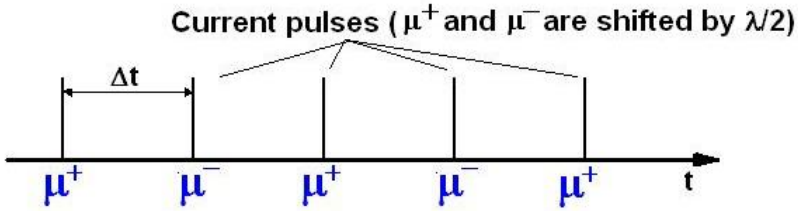


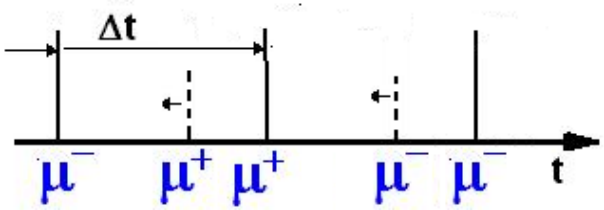
For N=2e12, f=1.3 GHz
(ILC-like structure)
and σ=8 mm W_{max}= 6.2 MV/m!

N.Solyak
V.Yakovlev

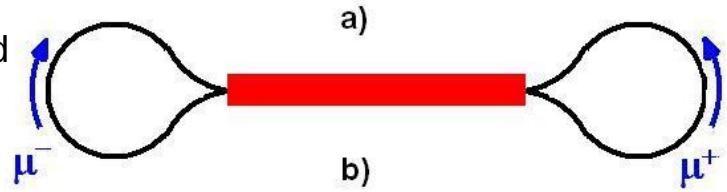
Bunch timing issues

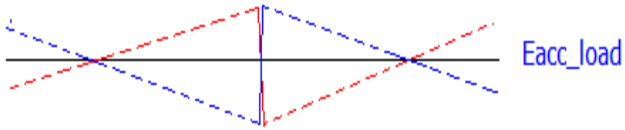
Preferred by RF

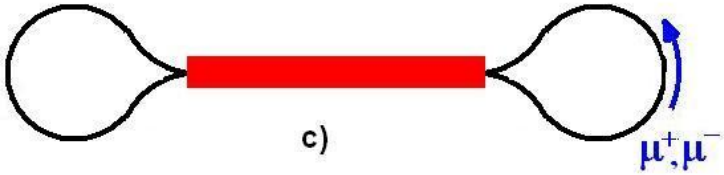




Preferred machine design







(Separate arcs for μ^+ and μ^-)

Acceleration gradient along linac,
Red -one direction,
Blue-opposite direction

N.Solyak
V.Yakovlev

MCTF

Total power estimates

	MC1999	HE2008	LE2008
Collider cm Energy (TeV)	3	1.5	1.5
Luminosity (1e34)	7	1	3
Emittance (pi mm mmrad)	50	25	2.1
Rep rate (Hz)	15	13	65
Muons/beam (1e12)	8	2	1
PD beam power (MW)	4	4	3.6
Muon beam power (MW)	57.6	6.24	15.6
TOTAL wall plug power (MW):	204	65	145
PD (MW)		16	68
Bunching Ring(s) (MW)		4	4
Target station (MW)		1	1
Collection system (MW)		4	4
Cooling system (MW)		4	2
Acceleration (MW)	130	30	60
Beamlines		2	2

APC

First look at RLA power requirements

N.Solyak
V.Yakovlev

HE2008, 1.5 TeV

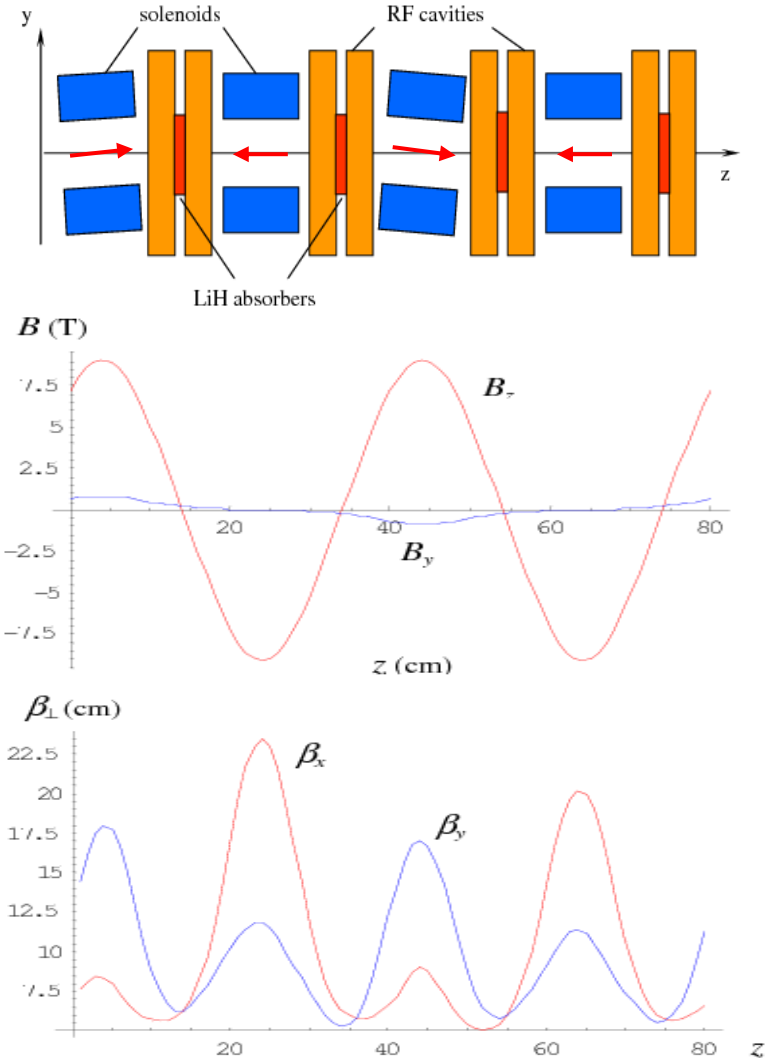
N	Muon losses, %	RF power, MW	Total cryogenic losses, MW	Losses in HOM couplers, MW	Total power MW	Number of klystrons (10 MW)	Number of cavities	Average klystron power, kW
10	6.4	20	4.8	1.5	24.8	180	2920	59
20	9.3	16	3.8	2	19.8	122	1460	70
30	11.1	14	3.5	2.2	17.5	92	973	81

LE2008, 1.5 TeV

N	Muon losses,%	RF power, MW	Total cryogenic losses, MW	Losses in HOM couplers, MW	Total power, MW	Number of klystrons (10 MW)	Number of cavities	Average klystron power kW
10	6.4	68	13.9	1.8	81.9	90	2920	402*
20	9.3	48.6	8.7	2.5	57.3	61	1460	424*
30	11.1	42	7.4	2.8	49.4	46	973	486*

Available 10 MW klystrons have an average power of 150 kW.

New cooling channel idea: FOFO snake



800MHz p=100MeV/c case :

Cooling by GH_2 (19% of LH_2) + LiH wedges

Bmax= 9.5T → tunes >1 → $\alpha_c > 0$

Solenoid tilt ±65mrad → Dmax ~ 6cm

Emax= 50MV/m

$Q_{I,II,III}$ =1.42+0.005i, 1.51+0.005i, 0.19+0.004i

- emittance damping length ~13m

Equilibrium $\varepsilon_\perp$~0.8mm, $\varepsilon_{||}$~0.4mm

Could potentially cool both charges in same channel!

Things to do:

- **Check with ICOOL or G4BL**
- **200MHz p=215MeV/c design for initial cooling.**

Estimated performance:

$\varepsilon_\perp$, $\varepsilon_{||}$ ~ 2cm → 5mm in 140m (10% decay loss)

- **Tilt 2nd and 4th solenoids horizontally (and displace all solenoids from axis) to make a helix.**

Hopefully α_c will become large enough to discard LiH wedges → smaller emittances

Y. Alexahin

HCC “rules of thumb”

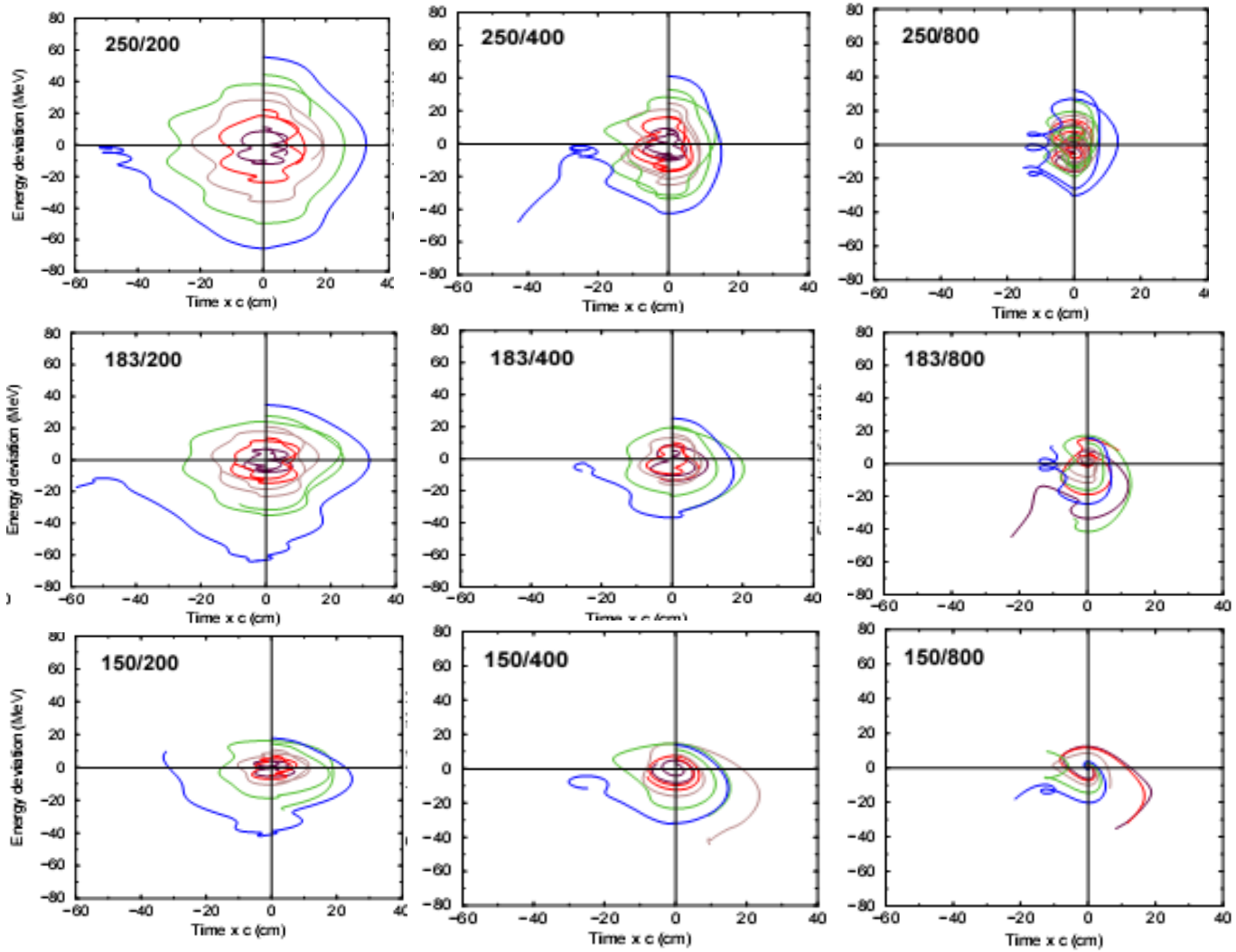
Independent investigation of HCC by Balbekov shows that:

- Equilibrium emittance is proportional to helix period (and is higher for HCC compared to e.g. Guggenheim lattice).
  - 1-2mmrad at 1m helix and 250MeV/c
- There is an optimal ratio between RF frequency and helix period. The cavity size roughly scales with the helix period.
  - 200MHz @ 1m, 400MHz @ 50cm, etc
- Obtainable cooling factor (ratio of acceptance and equilibrium emittance) is ~4.5 in each plane, 6D cooling ~90x.
  - Further cooling requires shorter helix (higher B field and RF frequency).

V. Balbekov

MCTF

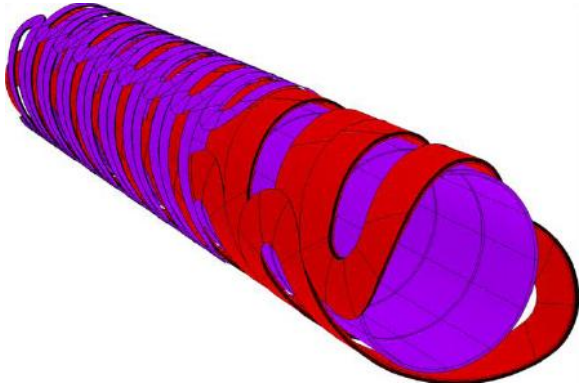
Frequency and energy dependance

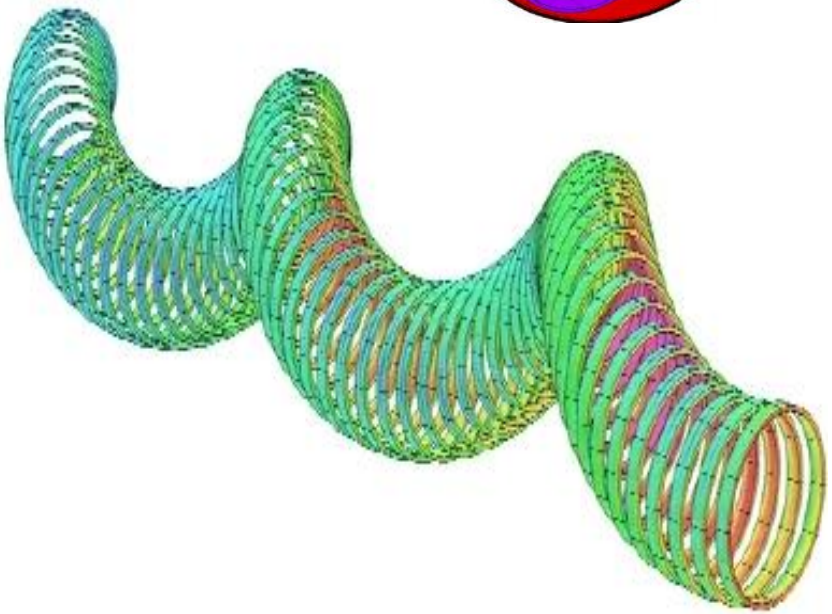


V. Balbekov

HCC magnet design

- HCC requires superimposed solenoid, helical dipole and helical quadrupole fields
- Helical solenoid (HS) use smaller coils than a “traditional” design
  - Lower peak field
  - Less stored energy
  - Lower cost
- Field components in HS determined by geometry
  - Over constrained
  - Coil radius is not free parameter



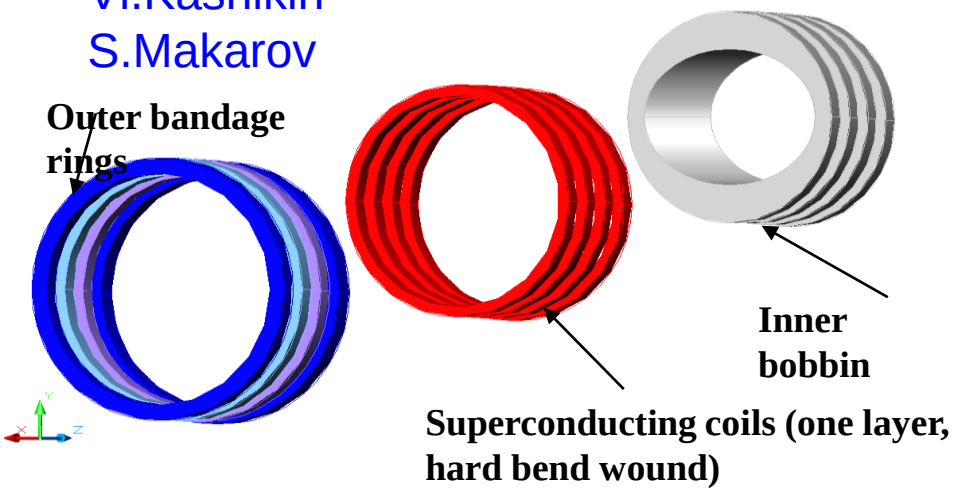


Vl.Kashikin

4-coil Helical Demonstration Model

- Goals:
  - validate mechanical structure and fabrication methods
  - study quench performance and margins, field quality, quench protection
- Features:
  - use existing SSC cable
  - fields and forces as in the HS for CDE
- Funded by MCTF and Muons Inc.

Vl.Kashikin
S.Makarov



Parameter	Model Nominal	Model Max	MANX
Peak superconductor field	3.3 T	4.84 T	5.7 T
Current	9.6 kA	14 kA	9.6 kA
Number of turns/section	10	10	10
Coil inner diameter	420 mm	420 mm	510 mm
Lorentz force/section, Fx	70 kN	149 kN	160 kN
Lorentz force/section, Fy	12 kN	25 kN	60 kN
Lorentz force/section, Fxy	71 kN	151 kN	171 kN
Lorentz force/section, Fz	157 kN	337 kN	299 kN

4-coil fabrication status

Vl.Kashikin
S.Makarov

Parts:

- design complete
- procurement in progress

Cable:

- Extracted strand samples were tested

Practice winding complete:

- cable stability and support during hard bend winding
- coil size control

Instrumentation:

- development started

Model test:

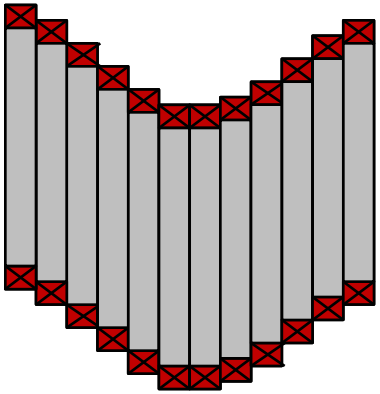
- September 2008

HCC demo experiment plans

- Before building a large (and expensive) HCC magnet, would like to know
  - How we can include RF in a HCC without loosing cooling performance
  - If HPRF works with beam
- The next step would likely be to build a section of such a channel, as an engineering demo.
- A HCC 6D cooling experiment, with or without RF, would happen later.

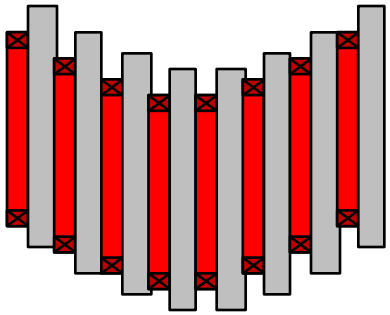
How to implement a real HCC?

"Type I"



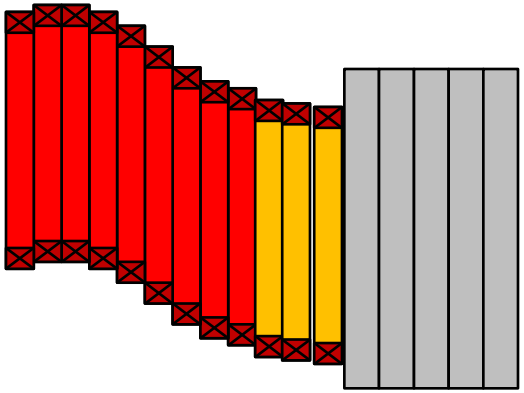
- RF inside coil
- Highest possible RF packing factor
- Cavity must be smaller than the coil -> high frequency

"Type 2"



- RF between coils
- Lower RF packing factor
- Difficult H2 cryostat design and assembly

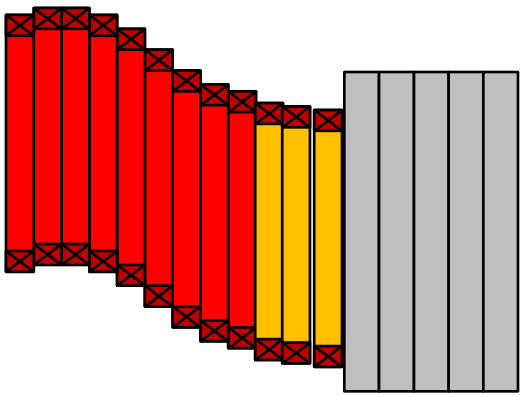
"Type 3"

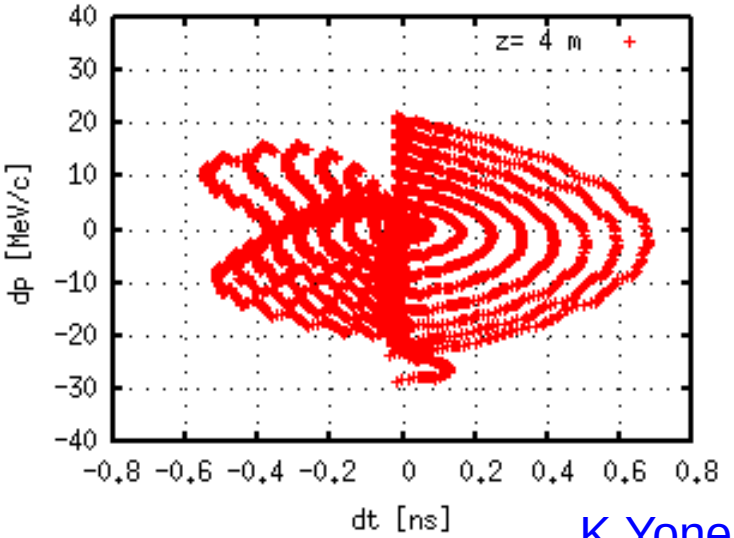


- RF and coils separated
- Lower RF packing factor
- Requires some kind of matching between sections
- Likely easier to build and maintain.

Type 3: Separate RF and helical solenoid

- To be efficient, would need a short(er) matching section.
- Problem: time-of-flight spread in helical section too large to recapture.
- Solution may exist, but not found yet.

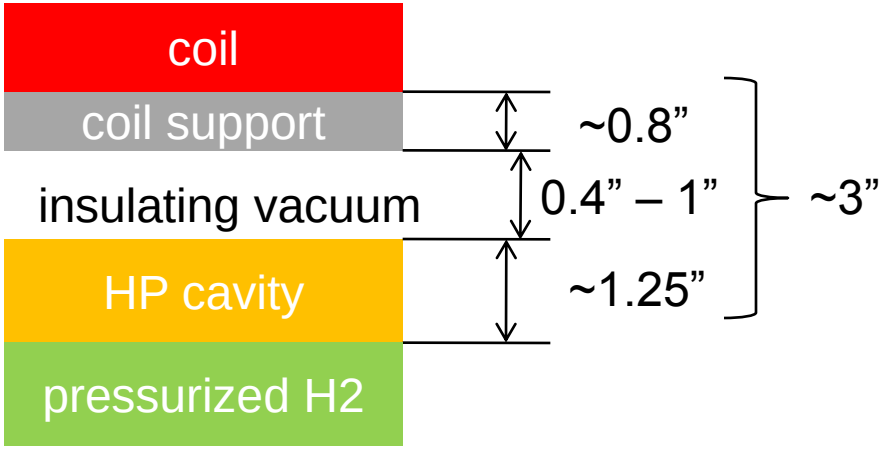




K.Yonehara

Required clearance

- Coil and cavity at different temperatures require insulating vacuum gap.
- Estimated required clearance ~3”
  - This does not include any RF feed
- Compare to HP H_2 cavity radius at various frequencies
  - Only low frequency version appear to be plausible.

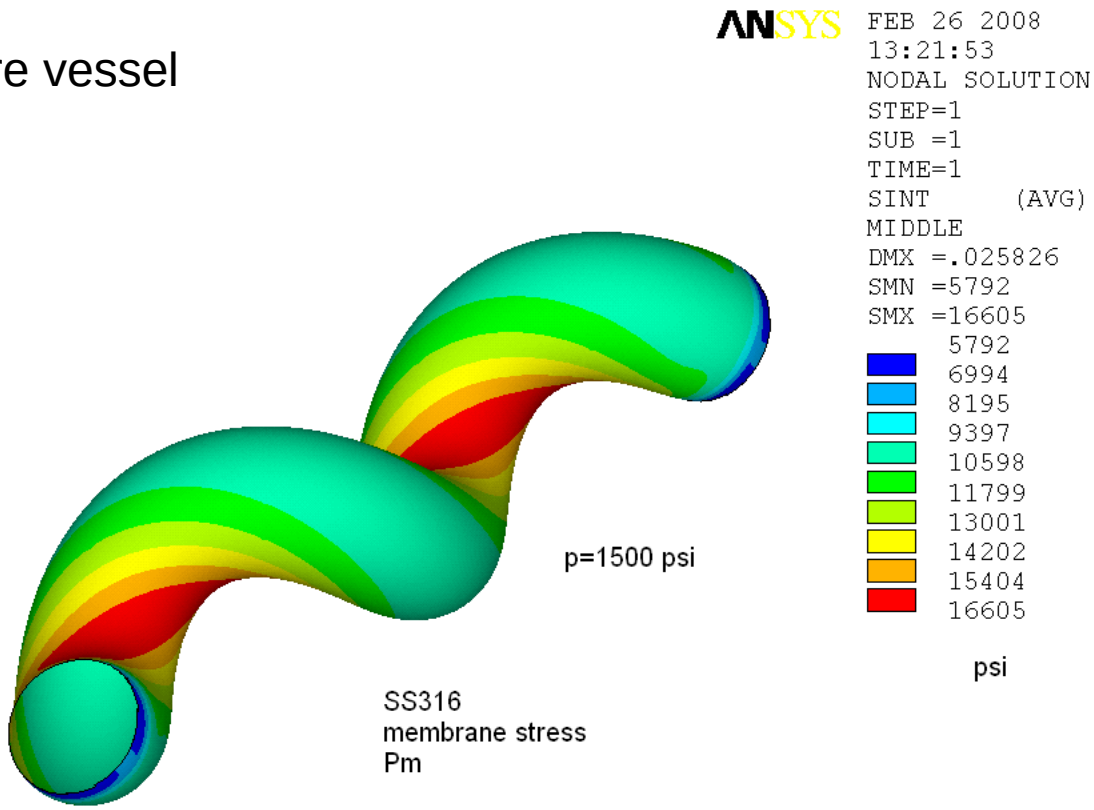


Frequency	Cavity Radius	ratio
200 MHz	55cm (22”)	88%
400 MHz	28cm (11”)	78%
800 MHz	14cm (5.6”)	65%
1600 MHz	7cm (2.8”)	48%

(assuming 200atm H_2)

Ansys stress simulation

Helical pressure vessel

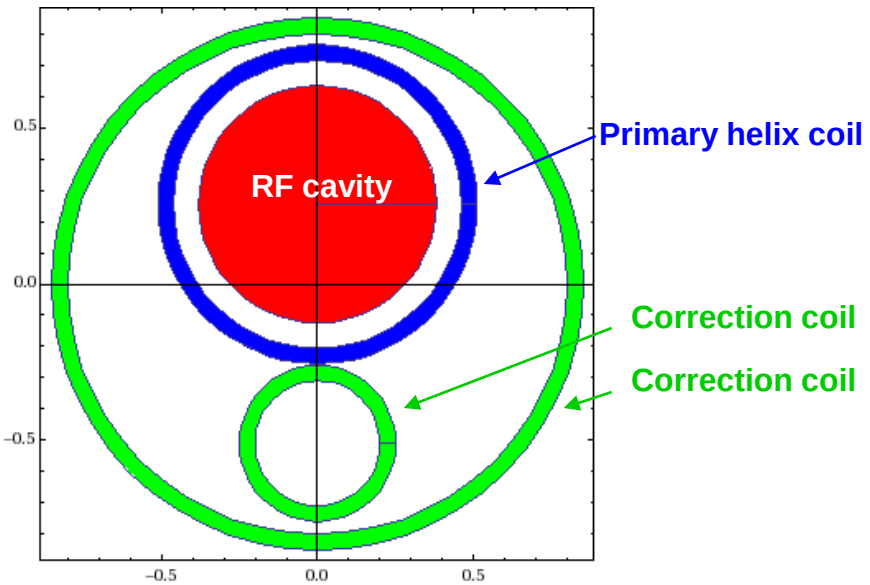


SS316,p=1500 psi,t(shell)=1.25 ",tend=2"

A.Lee

Helical Solenoid with correction coils

- At least for later stages of HCC, we will need correction coils
- Relax geometric constraints e.g. by
  - Overall solenoid for tuning of B_z component
  - Additional helical correction coil(s)for tuning dipole and quad component.
- Dielectrics inside the cavity could reduce cavity size

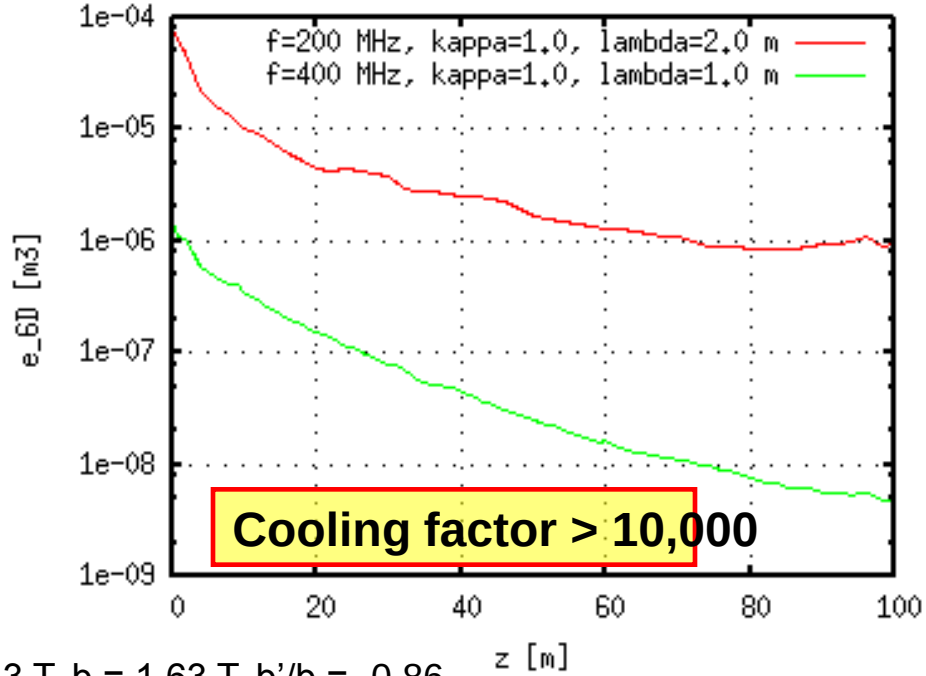


K.Yonehara

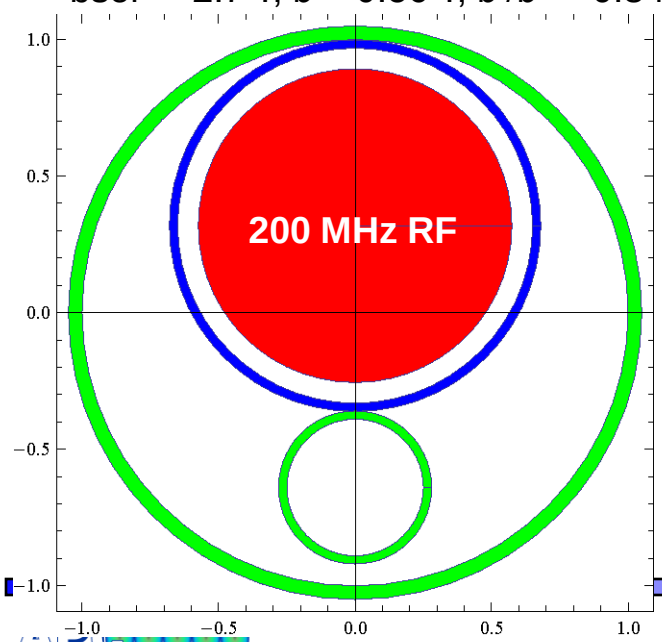
MCTF

Series of HCCs

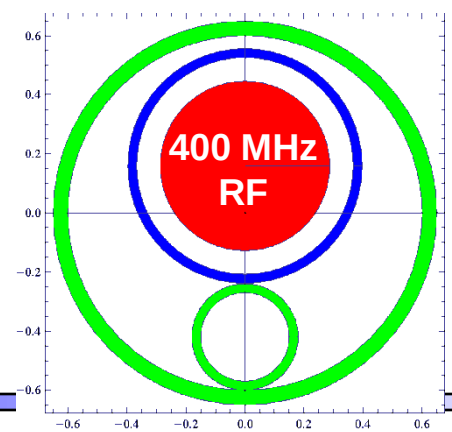
1st HCC: λ=2.0 m, κ=1.0
Primary HS:
Inner R = 650 mm, Outer R = 680 mm
Current density = -69 A/mm2
Correction HS:
Inner R = 250 mm, Outer R = 280 mm
Current density = 414 A/mm2
Solenoid:
Inner R = 1000 mm, Outer R = 1050 mm
Current density = -11 A/mm2



bsol = -2.7 T, b = 0.86 T, b'/b = -0.84



bsol = -5.3 T, b = 1.63 T, b'/b = -0.86



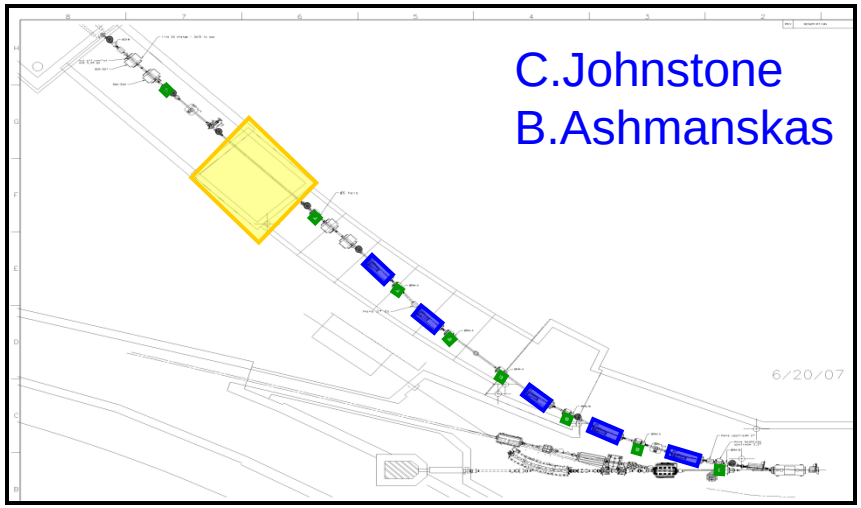
2nd HCC: λ=1.0 m, κ=1.0
Primary HS:
Inner R = 367 mm, Outer R = 397 mm
Current density = -129 A/mm2
Correction HS:
Inner R = 150 mm, Outer R = 180 mm
Current density = 387 A/mm2
Solenoid:
Inner R = 600 mm, Outer R = 650 mm
Current density = -31 A/mm2

HCC plans

- Now have estimate of required HCC bore to fit HPRF and insulation inside.
- Next step will be to ask TD magnet experts to design large bore magnet with optimal correction coil scheme, in particular for the last HCC section.
- In parallel, develop a real RF cavity design to fit in this space.
- If a promising solution is found, would like to build a section with RF and test.

MTA beamline

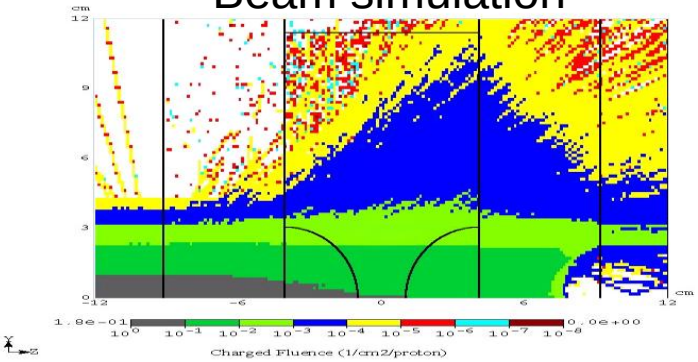
- HPRF test with beam is critical!
- MTA beam line major activity and budget item this year.
- Switching C-magnets ready to be installed in few weeks
  - Linac access required
- RF waveguide reconfiguration required for beam into hall

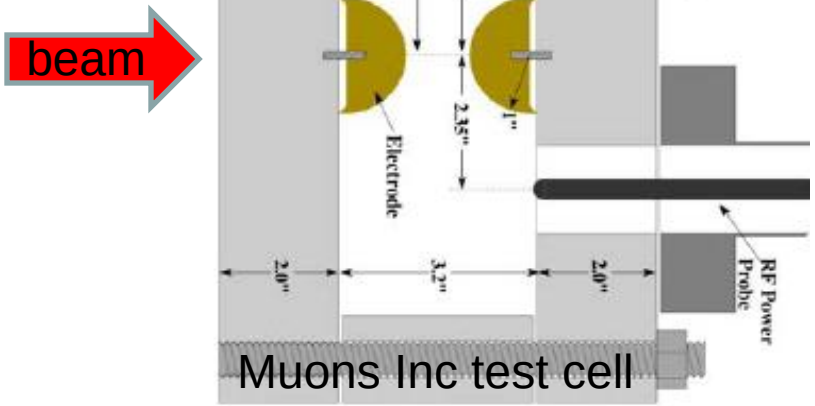


First HPRF experiment

- Beam tests will be done in collaboration with Muons Inc
- First test will use the existing Muons Inc test cell
  - Will indicate direction of follow-ups experiments
- Linac 400MeV proton beam can generate ionization levels similar to muon beam.
  - 6e12 protons ~1.2e13 muons
- Recently approved SBIR Phase I with Muons Inc.

Beam simulation

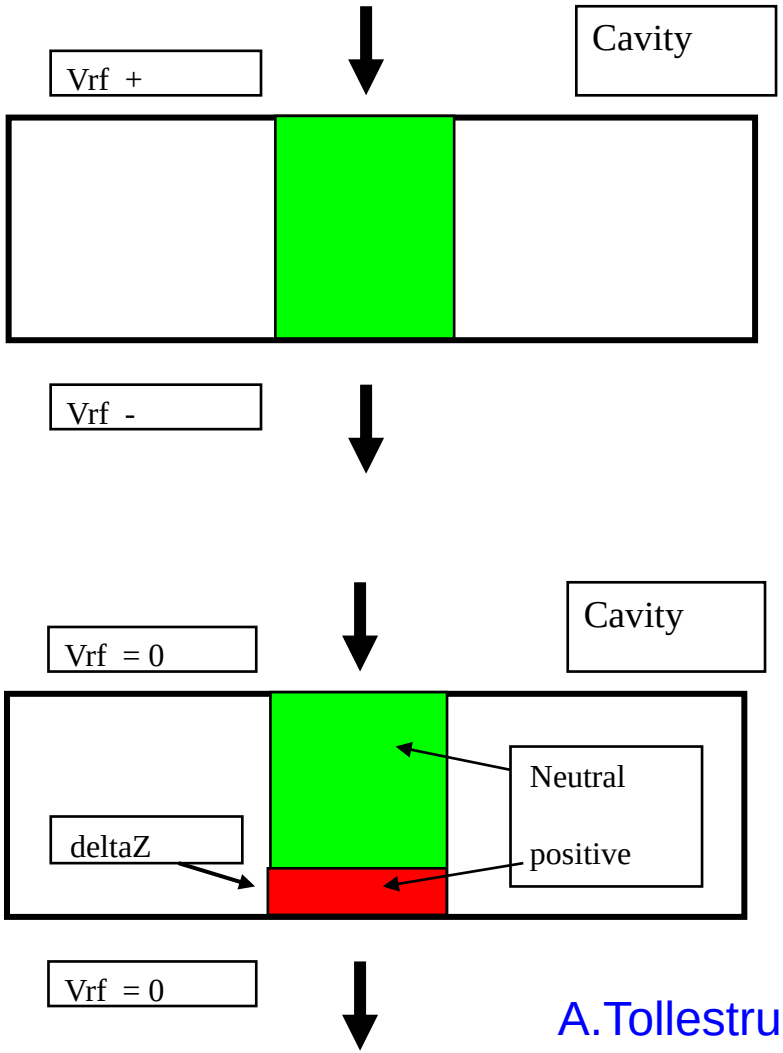




Muons Inc test cell

What we expect to happen?

Assume beam passes thru cavity at max Vrf as a delta function



After a ¼ cycle the electrons have all drifted upward by a distance deltaZ. This discharges the top plate and leaves a layer of positive charge against the bottom. The field in this region remains the same and the field outside decreases. A ¼ cycle later the image is reversed.

A.Tollestrup

MCTF

HCC example

A.Tollestrup

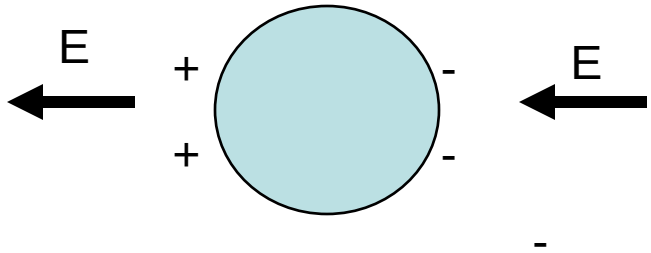
Emittance	4.3 mm rad	1.5 mm rad	.91 mm rad
Freq	400 Mhz	800 Mhz	1600 Mhz
Gradient	16 MV/m	16 MV/m	16 MV/m
Beam rms r	27.6 mm	12.8 mm	7.6 mm
Cavity length	5.0 cm	2.5 cm	1.25 cm
Q from plasma	360	157	111
Joules Cav	3.95	.49	.0616
Delta Vrf / Vrf	1 E-4 1.6 E-3	2 E-4 3 E-3	9 E-4 1.4 E-3
Cavity Q no mu	12886	9112	6443
Q[1], Q[16]	5805 628	3343 318	1873 161
P cavity kw	261	249	309
P gas 1 & 16	939 kw 15 mw	469 kw 7.5 mw	235 kw 3.76 mw

How to remove the ions?

A.Tollestrup

1. If all of the electrons were swept out leaving only the positive ions, the radial field would be of the order of 10^9 volts/meter! A sweep field might be 100 V/cm and will be neutralized inside the plasma. See figure below. It isn't clear whether the sweep field or diffusion will predominate in the expansion of the charges. At these high densities, at this low E field the electron velocity is of the order of 1000 cm/sec.

2. 10 e11 muons going thru a 2.5 cm cavity with hydrogen density .017 grm/cm^3 generates a total charge of 90 micro Coulombs. If this could be swept out in 1 ms the current would be 90 ma.



The electric field lines simply terminate on the plasma. I think the main way the ions disappear is thru diffusion to the walls. This is a slow process.

Surface charge = $\varepsilon_0 E$; For instance 100 KV/meter requires a surface charge of 88 pC /m^2

A factor of 10^6 less than the total charge in the ions.

Some questions that need answers:

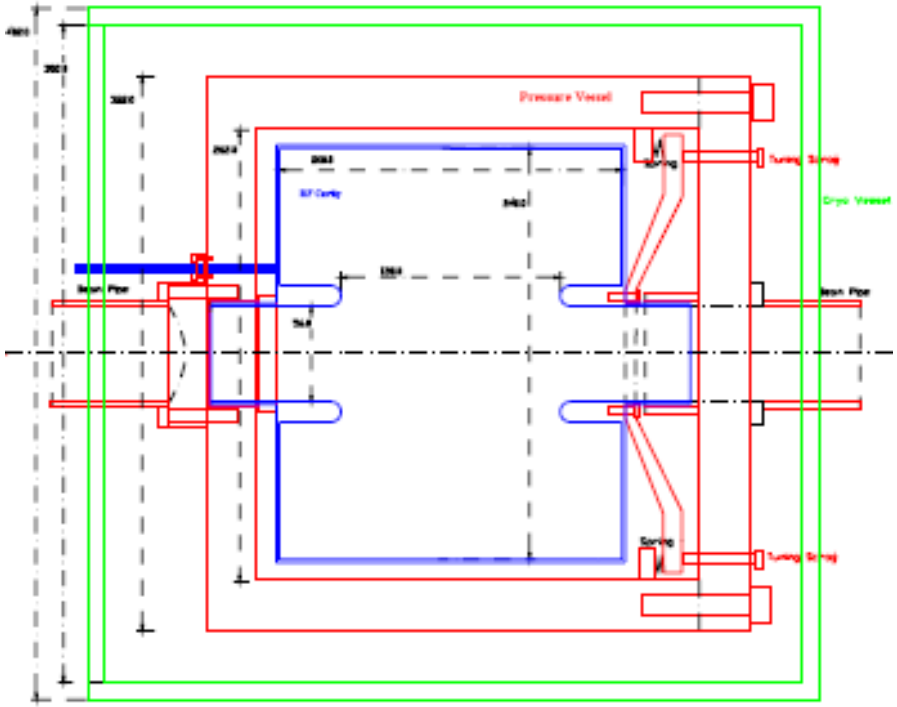
A.Tollestrup

- 1. Does something unexpected cause breakdown? The gas is from the Pashen limit but there could be local action at the cavity surfaces that initiate breakdown. In general we need experiments to validate our theoretical models.
- 2. The free electrons load the cavity. 10e11 looks like near the limit. Can the electrons be captured fast enough to form negative ions and eliminate this loss by something like SF_6? (Note: SF_6 not suitable!)
- 3. How does one get rid of the negative ions if one does the above.

Follow-up cavity

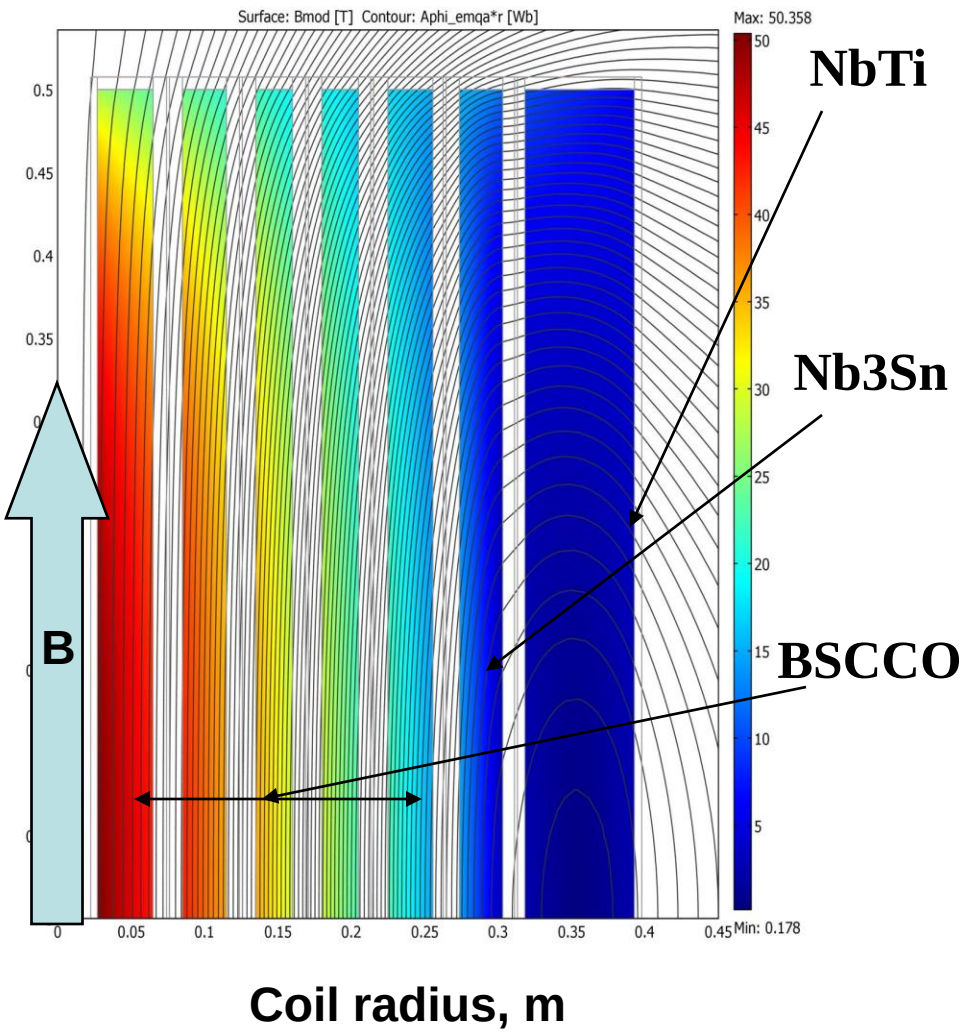
- Test cell is not an accelerating cavity.
- Several effects we will not be able to study
  - Scaling with pressure
  - Are the ions a problem?
- Build dedicated cavity!
- Will require MCTF resources in FY09.
  - Scale ~1 FTE + ~$200k
  - Muons Inc Phase II SBIR?

M.Popovic



Tunable HP cavity

50 T Solenoid Conceptual Design Study



Key design issues:

- superconductor Jc
- effect of field direction on Ic in case of HTS tapes
- stress management
- quench protection
- cost

Solutions:

- hybrid coil design
- coil sections

Va.Kashikin

Towards a National HTS collaboration

- **Development of NbTi and Nb_3Sn based magnets were developed thru a very successful collaboration between the University Community, the National Labs and the Conductor Manufacturers.**
- **The High Temperature Superconductors operated at LHe temperature offer new and exciting opportunities for magnet design.**
- **Alvin has pushed for a National HTS Collaboration to develop and exploit these possibilities:**
  - **High field solenoids, dipoles, and quadrupoles for HEP**
  - **NRC panel COHMAG (Committee on High Magnetic Field Research and Technology) set 30 T goal for new NMR and magnets used in scientific studies.**

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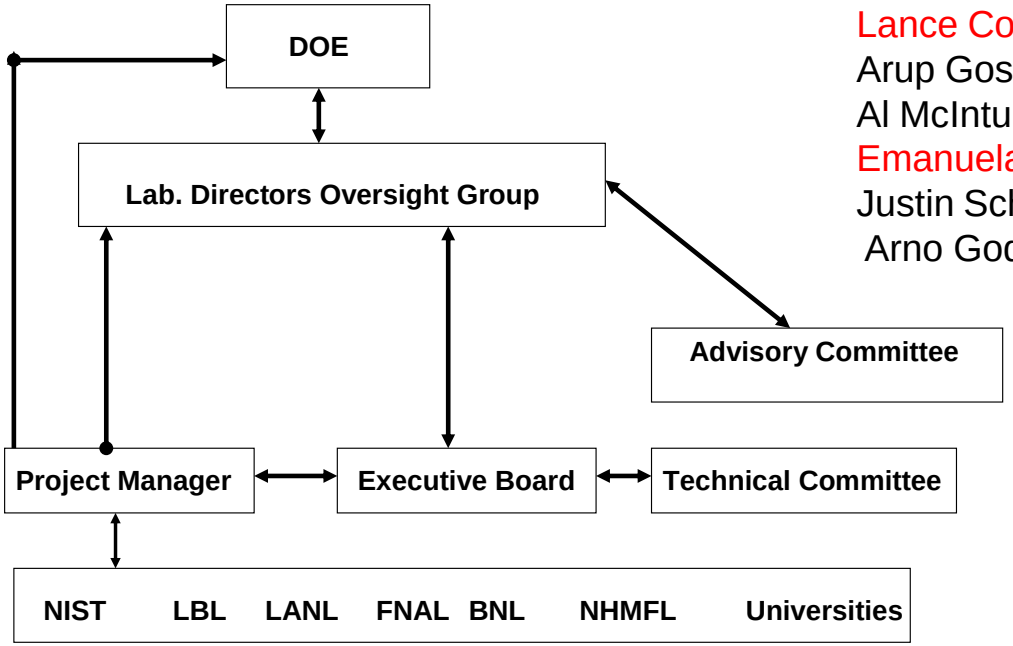
HTS collaboration structure



Technical Committee:

David L.arbalestier Ch.	NHFML
Dan Dietderich	LBL
Ken Marken	LANL
Lance Cooley	FNAL
Arup Gosh	BNL
Al McInturf	TA&M
Emanuela Barzi	FNAL
Justin Schwartz	NHFML
Arno Godeke	LBNL

Collaboration is taking form
Modelled after LARP and NFMCC.
Proposal to be submitted to DOE for $2M annual funding.

A.Tollestrup

HTS Collaboration target areas

- 1. Leakage.
- 2. Connectivity.
- 3. Dependence of J_c on angle wrt B.
- 4. Conductor insulation.
- 5. Containing the forces and controlling strain.
- 6. Quench protection.
- 7. Wind and React technology.
- 8. Cabling.
- 9. Radiation resistance.

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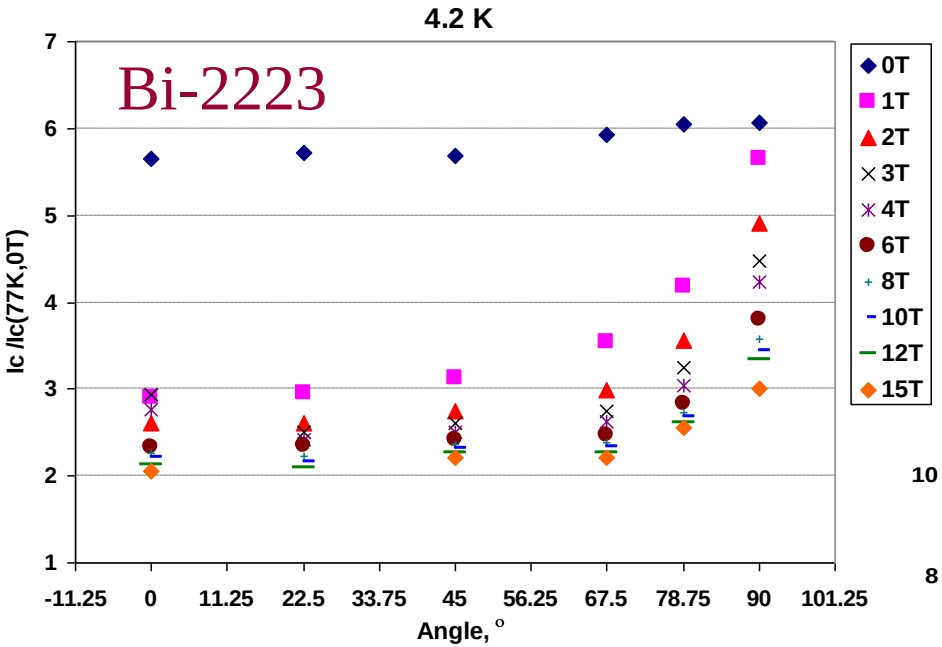
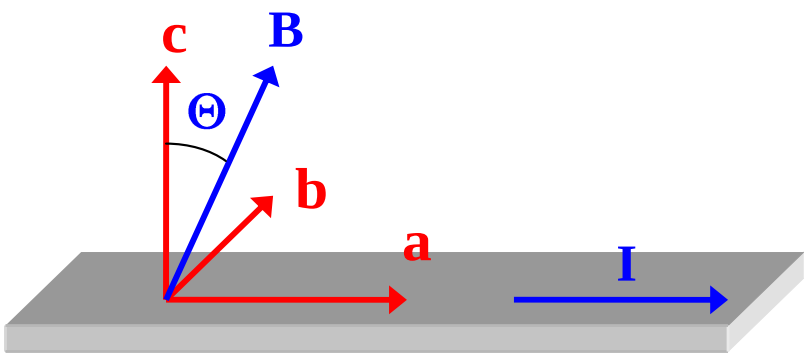
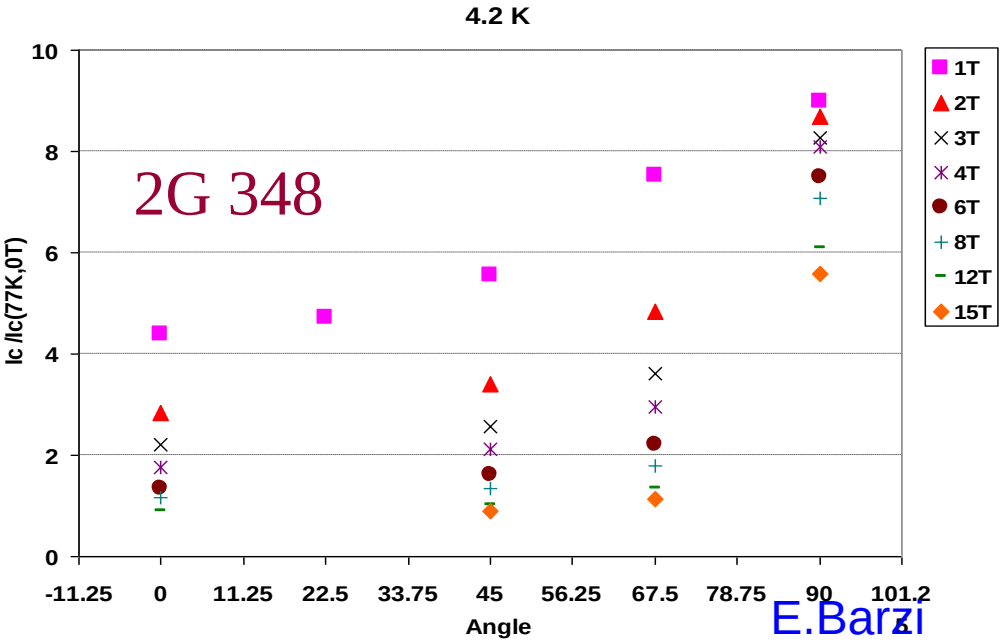
Ic Angular Dependence at 4.2 K





- Detailed measurement of Ic angular dependence for HTS tapes at fields up to 15-16 T
  - Most of the Ic reduction occurs between 90 and 45 degrees
- Important information for High Field HTS solenoid design study



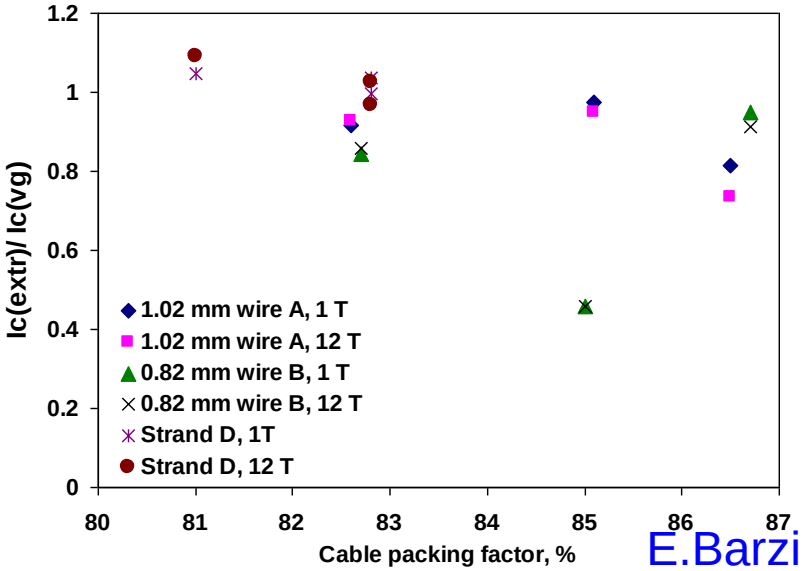
BSCCO Rutherford Cables

Goals:

- increase conductor Ic
- reduce magnet inductance
  - Important for magnet quench protection

Issues:

- Ic degradation after cabling
  - Determine design criteria and cabling procedures
  - low degradation at packing factors <87%
- Cable HT optimization
  - reduce Ag leaks and Ic degradation
- Transverse pressure sensitivity studies
  - determine pressure limits



E.Barzi

MCTF Summary

- Significant progress in many areas, despite difficult funding year
- Our most pressing short term goal is to test HP cavity with beam.
- We are also working towards integrating RF into a helical solenoid.
- HTS will be pursued by National Collaboration
- With NFMCC, developing a 5-year plan towards a feasibility study in 2012.

Useful references:

- MCTF web site:
  - http://mctf.fnal.gov
- BNL MC Design Workshop:
  - http://www.cap.bnl.gov/mumu/conf/collider-071203/
- NFMCC Collaboration meeting:
  - http://www.cap.bnl.gov/mumu/conf/MC-080317/
- MUTAC Review:
  - http://www.cap.bnl.gov/mumu/conf/MUTAC-080408/
- Low Emittance MC Workshop:
  - http://www.muonsinc.com/lemc2008/

Just some

BACKUP SLIDES

Balbekovs preferred HCC channel

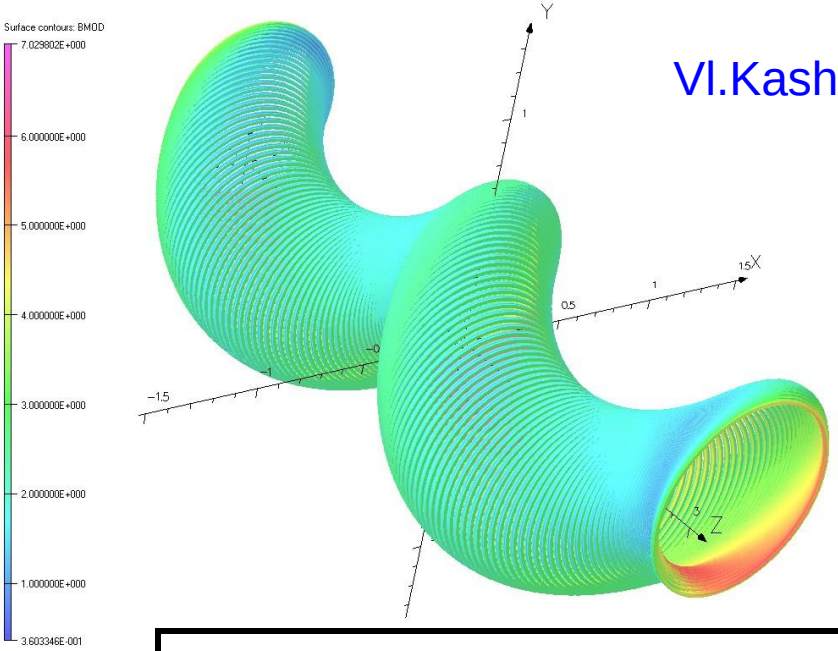
Period length is the most important HCC parameter which significantly predetermines other ones.

The most prospective investigated variants are summarized in table:

#	1	2	3
Period length (m)	1	0.5	0.25
Beam momentum (MeV/c)	250	183	183
Frequency (MHz)	200	400	800
Solenoid field (T)	6.96	10.2	20.4
Trans.emit1.init/fin (mm)	9.5/2.0	4.6/1.1	2.6/0.55
Trans.emit2.init/fin (mm)	9.0/1.9	4.6/0.95	2.3/0.48
Long. emit.init/fin (mm)	13./3.2	7.1/1.6	3.4/0.81
6D emit.init/fin (mm^3)	1100/12	150/1.6	20/0.22
Transmission (%)	87	75	73

V. Balbekov

80cm bore HCC



Vl.Kashikin

Helical Solenoid Parameters:

Helix orbit radius 0.255 m

Coil inner diameter 800 mm

Superconductor NbTi

Current 9.7 kA

Helix period 1.6 m

Helix pitch 1.0

Solenoid length 3.2 m

Coil max flux density 7.0 T

Field components, R=0.255m, z=1.6 m	HS	K.Y.
Bz, T	-4.76	-
Dipole Bd, T	1.074	1.05
Gradient dBt/dr, T/m	-0.47	-0.45
Solenoidal, T	- 3.64	- 3.35

K.Yonehara