Superconducting Cable-in-Conduit: new technology to enable FNSF

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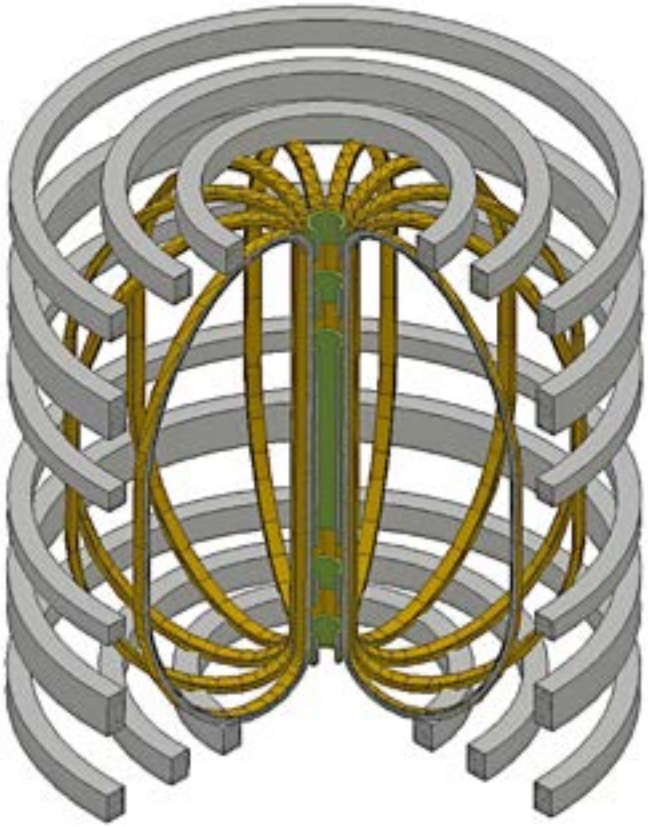
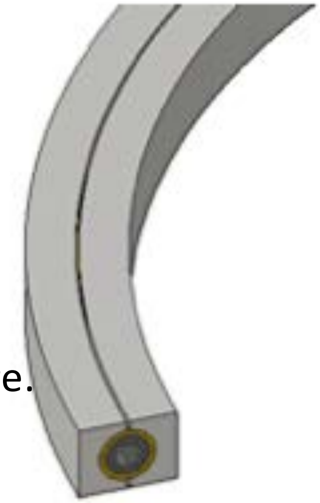
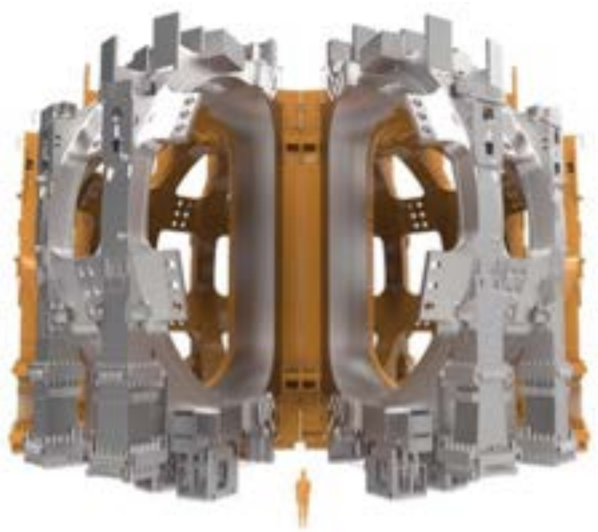


- Magnetic confinement needs more field in less space.
- ***SuperCIC*** preserves full performance of superconducting strands
- ***SuperSheath*** preserves full strength of armor structure.
- ***Enables FNSF designs with high κ, β_N***
- ***Enhanced solenoid*** can provide same inductive heating as ITER in an ST topology.
- ***M&M vessel*** accommodates MA plasma currents, solves the nested winding woes.



Superconducting Cable-in-Conduit (CIC) was developed for tokomaks and energy storage



A ‘rope of ropes’ of superconducting wires is wrapped around a porous conduit, then sheathed in a high-strength alloy sheath, then formed to the contours for the solenoid and toroid windings. Nb_3Sn is used for high-field requirements, and the CIC winding must be heat-treated to ~650 C in final configuration.

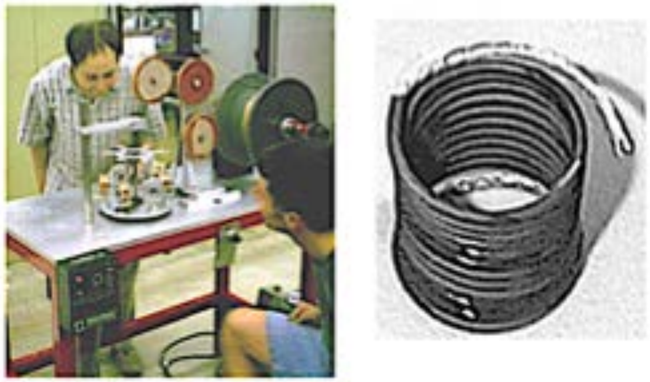
Several problems:

- ‘Rope of Ropes’ makes deformation and strain degradation of wires during cabling and high-field operation – get < half the performance.
- Sheath must be welded onto the cable, cable must be bent on arcs – heat-affected zone, embrittlement, residual strain compromise strength.

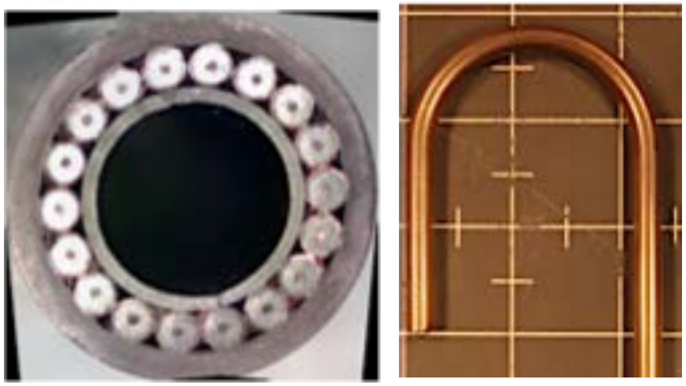
We have developed CIC conductor for SMES and for accelerator dipoles

- **1985:** 300 kA NbTi CIC developed and tested at the Texas Accelerator Center:

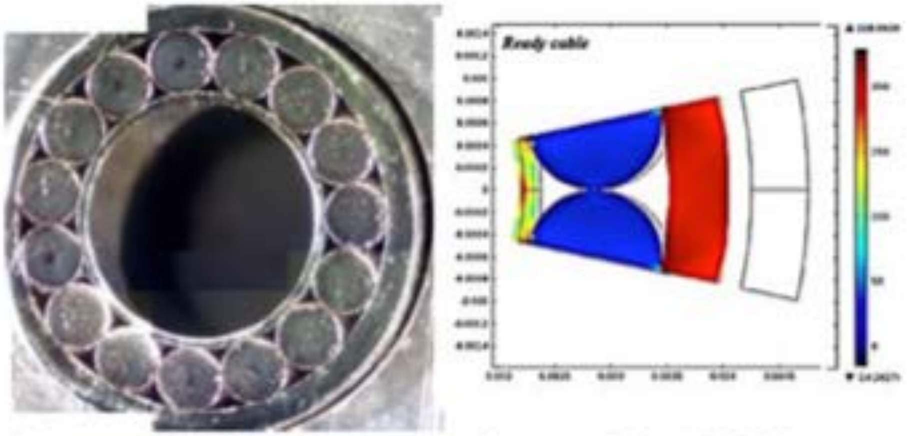
- **2000:** Bi-2212 CIC developed at the TAMU Accelerator Technology Lab for high-field dipoles for hadron colliders:



- **2015:** Nb_3Sn CIC developed at ARL for large-aperture superferric dipole for electron-ion collider:



The motivation in our CIC development is to preserve the full performance of all wires

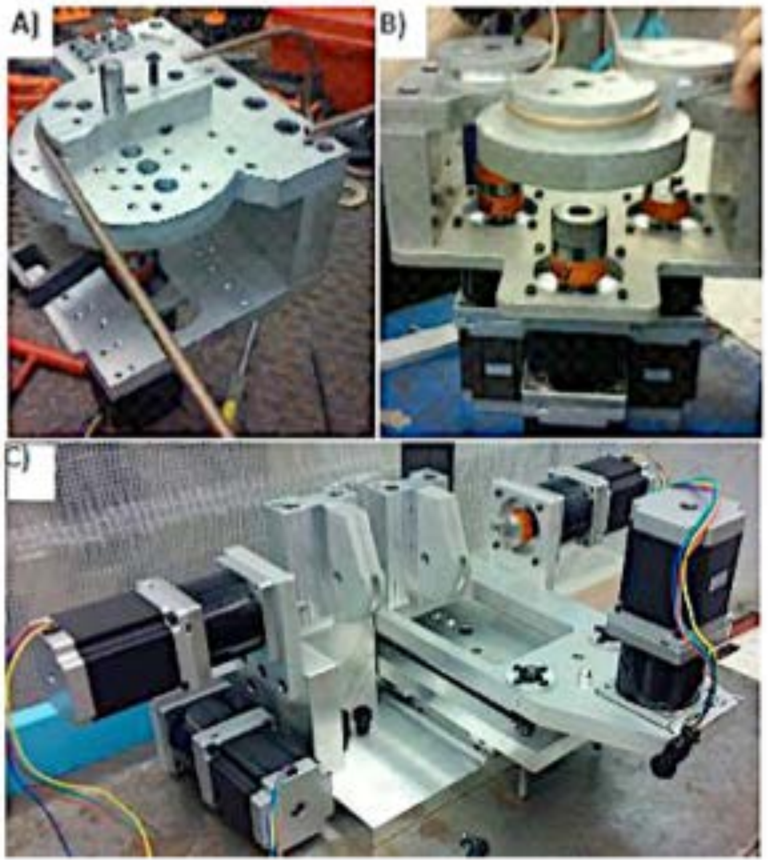


15-strand NbTi CIC conductor for JLEIC; b) FEA modeling of compression of sheath tube to immobilize strands.

Fabrication of 1- and 10-m CIC segments at ATC.

- A single layer of wires is cabled with twist pitch around a perforated thin-wall center tube.
- A SS foil tape is spiral-wound onto the cable and it is pulled into a seamless sheath tube.
- The sheath is drawn onto the cable to compress the wires against the center tube and immobilize them.

We have developed a coil technology that preserves full wire performance in a small-radius U-bend



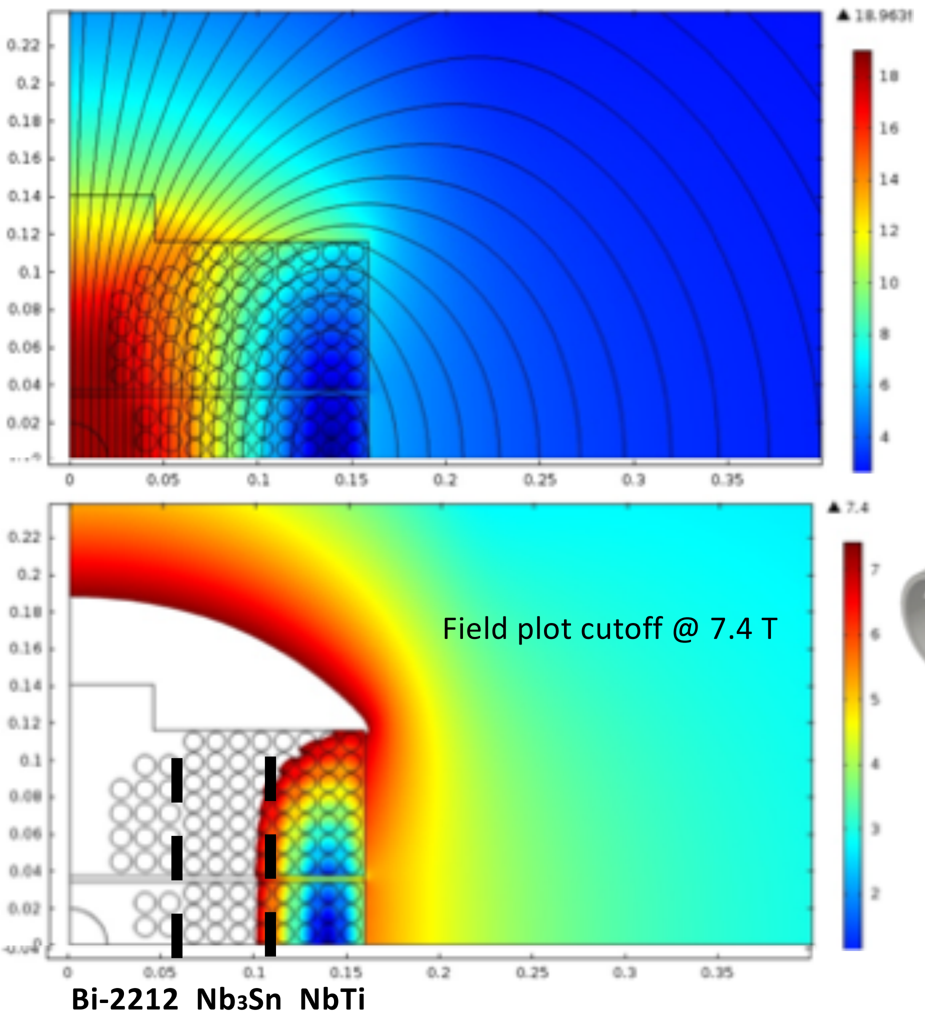
Motorized bending tools:

a) bender to form 180° U-bend while maintaining round sheath;
b) bender to form a dog-bone end for the sextupole winding turn;
c) bender to flare the U-bend to form a 90° end winding.

Completed 24-turn winding for 1.2 m dipole.

We have extended our single-layer CIC technology to make 2-layer CIC for high-current applications

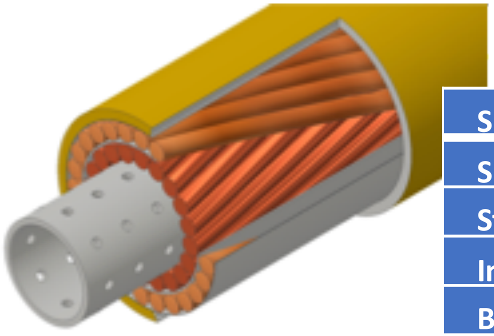
18 T hybrid dipole for an ultimate-energy hadron collider



This **18 T hybrid dipole** has three windings, nested one on the next.

The Bi-2212, Nb_3Sn, and NbTi windings are connected in series.

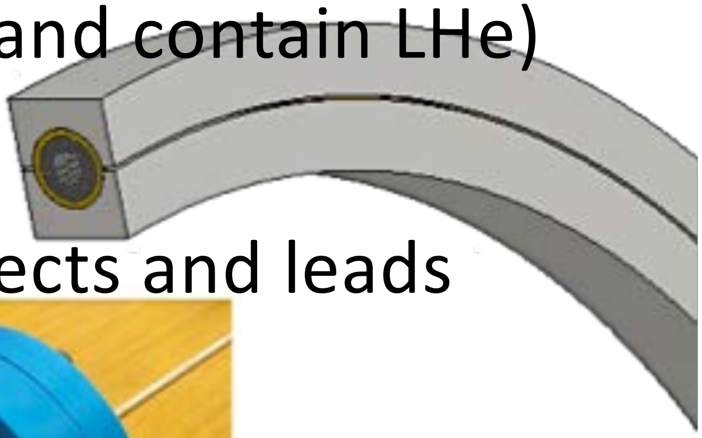
Extruded Ti channels locate and support all CIC turns in the winding. The sheath tubes on the CIC conductors make it possible to fabricate the windings separately (with flared ends), heat treat the Nb_3Sn and Bi-2212 windings separately, then assemble the 3 windings and preload them in the final assembly.



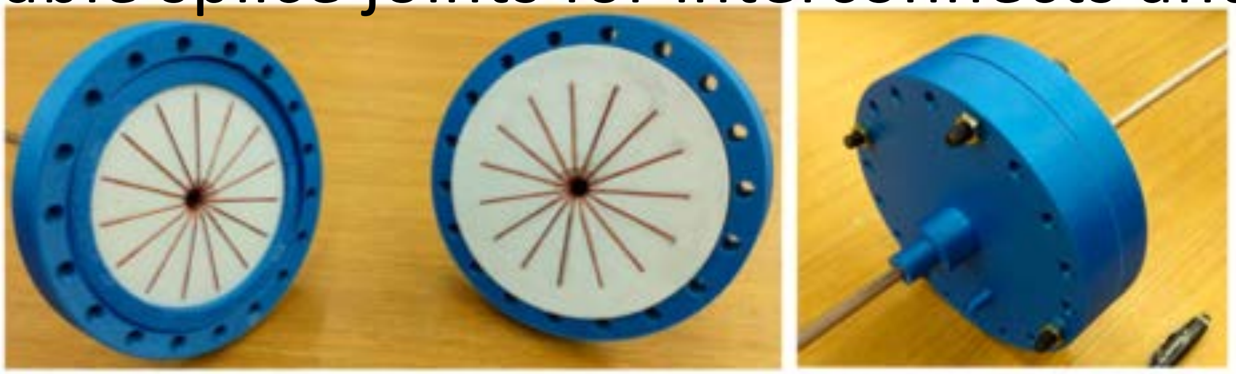
Short-sample I	26			kA
Short-sample B	18.1			T
Stored energy	6.3			MJ/m
Inductance	18			mH/m
Bore diameter	5			cm
Cables:	Bi-2212	Nb_3Sn	NbTi	
Strand dia.	1.0	1.0	1.0	mm
Cu/NonCu		1	1	
# strands	42	42	42	
Field @ conductor	19	15	7.4	T
#turns/bore	36	96	64	
Total wire area	24	66	44	cm^2

We are developing the cable and coil technology for a 40 kA SuperCIC

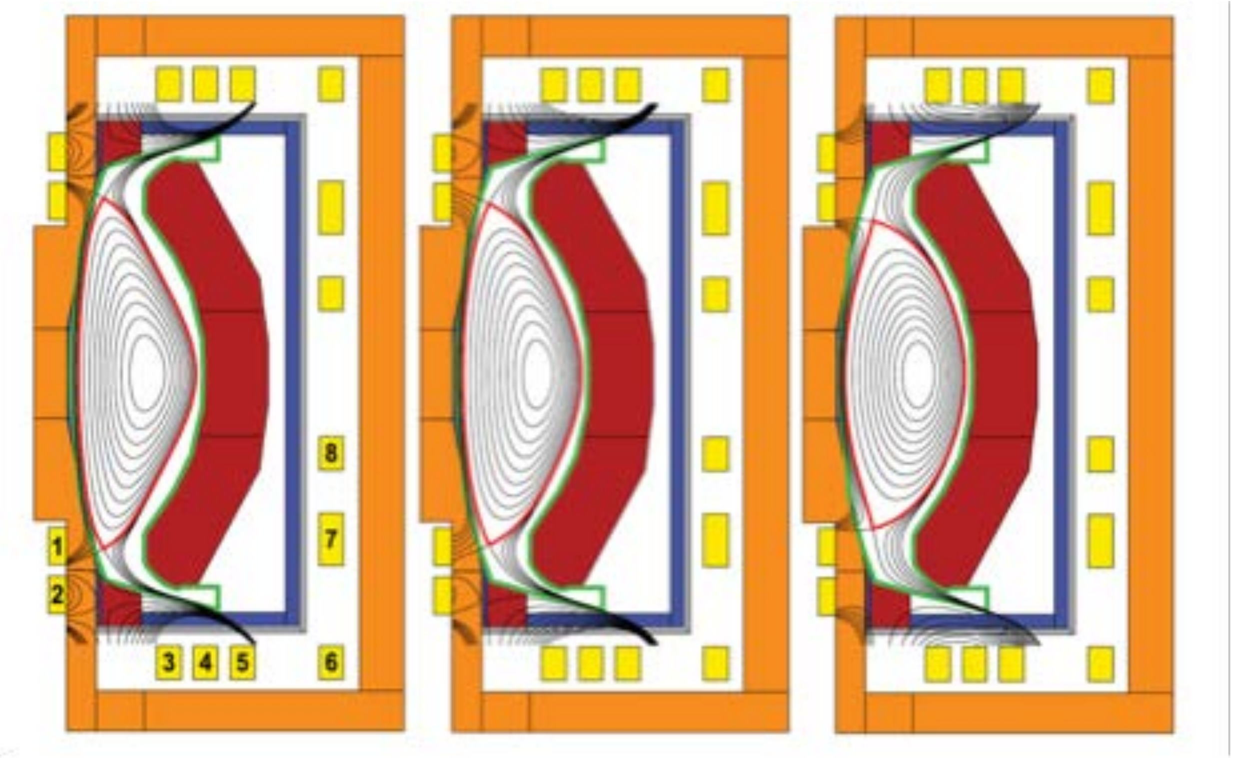
- 2-layer CIC using Nb_3Sn and Bi-2212 strands
- Capability to make U-bends on a 2” radius yet preserve I_c



- Separate the functions of armor (to manage Lorentz stress) and sheath (to immobilize wires and contain LHe)
- Demountable splice joints for interconnects and leads



Now consider how SuperCIC could be of service for the magnetics of FSNF options

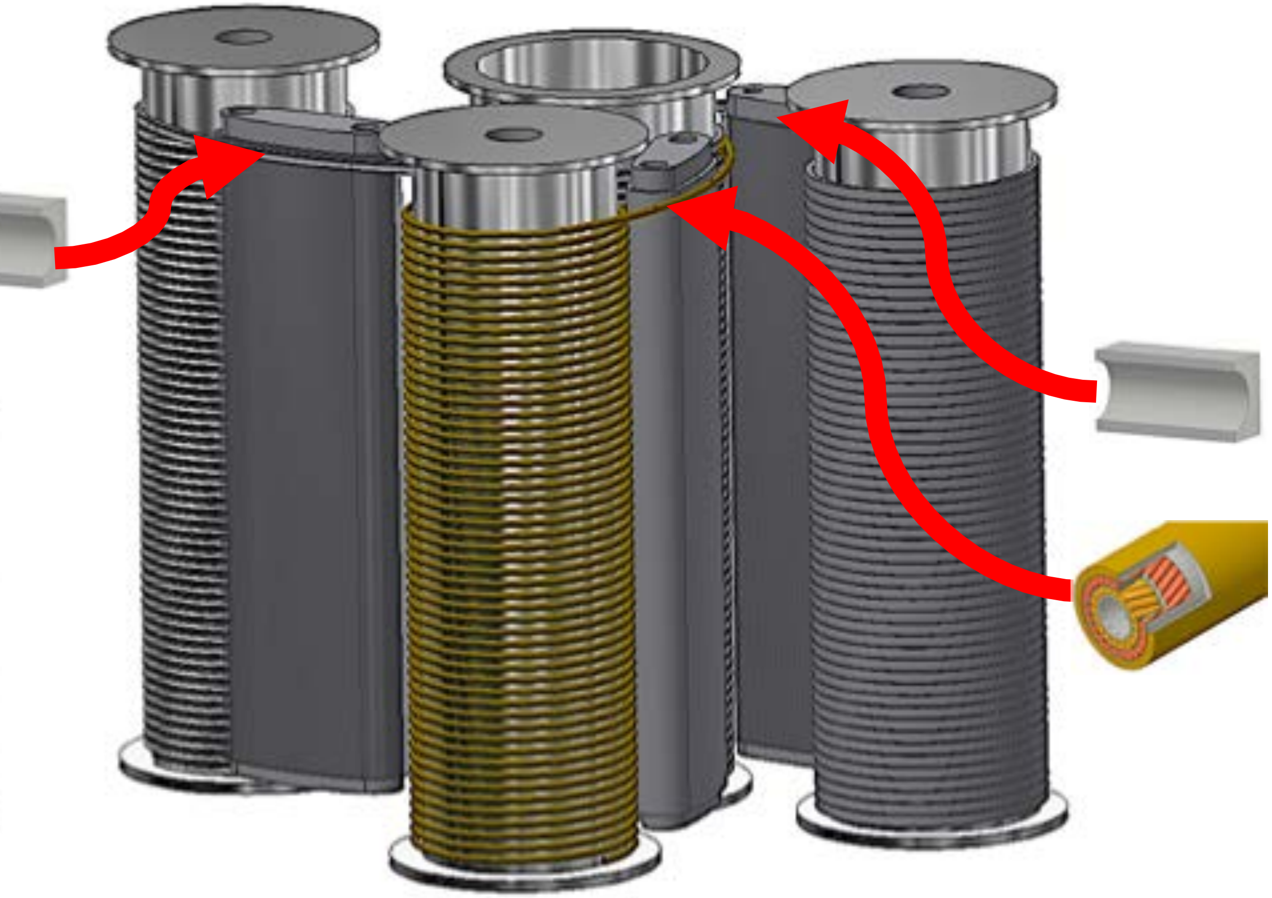


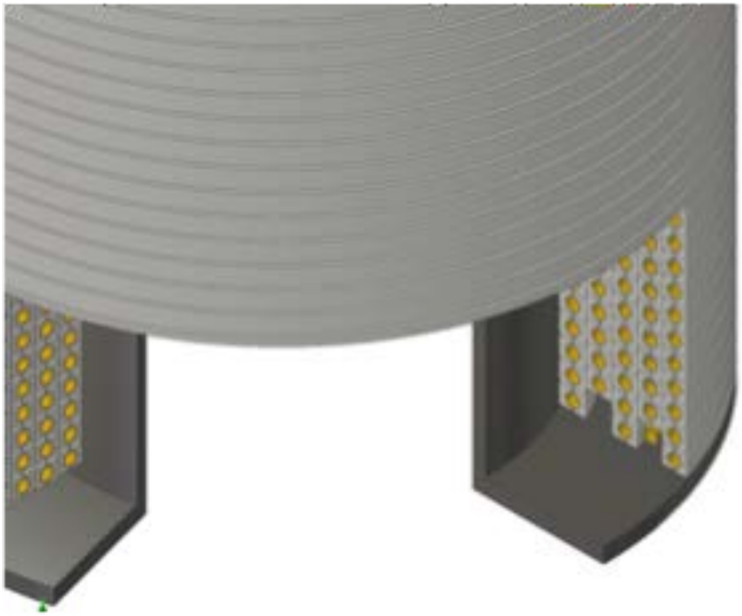
low l_i, high κ intermediate l_i, κ high l_i, low κ

Challenges:

- Solenoid is confined to small radius – low flux, so not much inductive heating.
- Poloidal windings require large current, size limits options for placement.
- Toroid windings are limited in strength by space available for inner-leg windings.

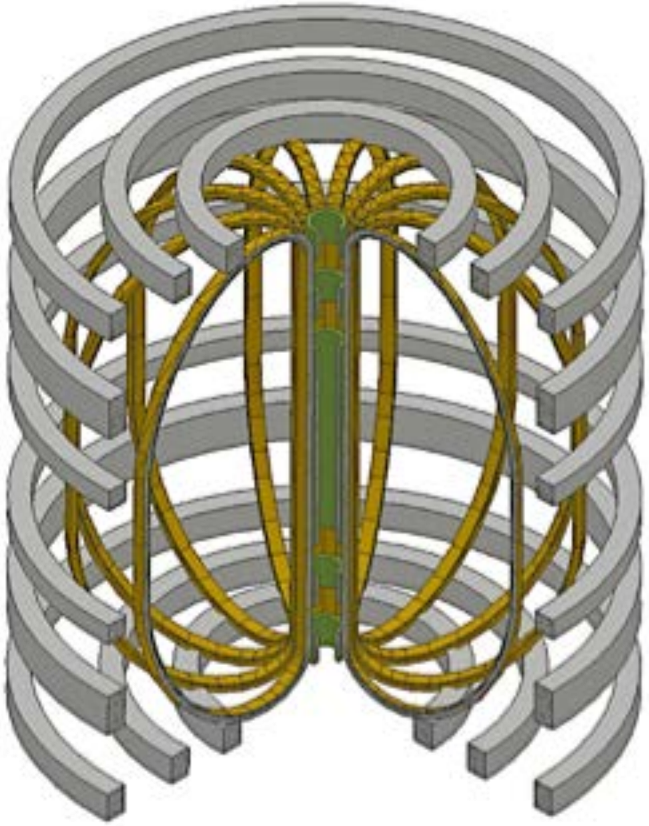
A SuperCIC solenoid can be wound with ~3x greater current density than with conventional CIC technology





- Lorentz stress is intercepted and bypassed through the matrix of co-wound armor elements.
- Each CIC cable feels only the Lorentz force acting on it.
- LHe flow and containment is handled by CIC, not armor.

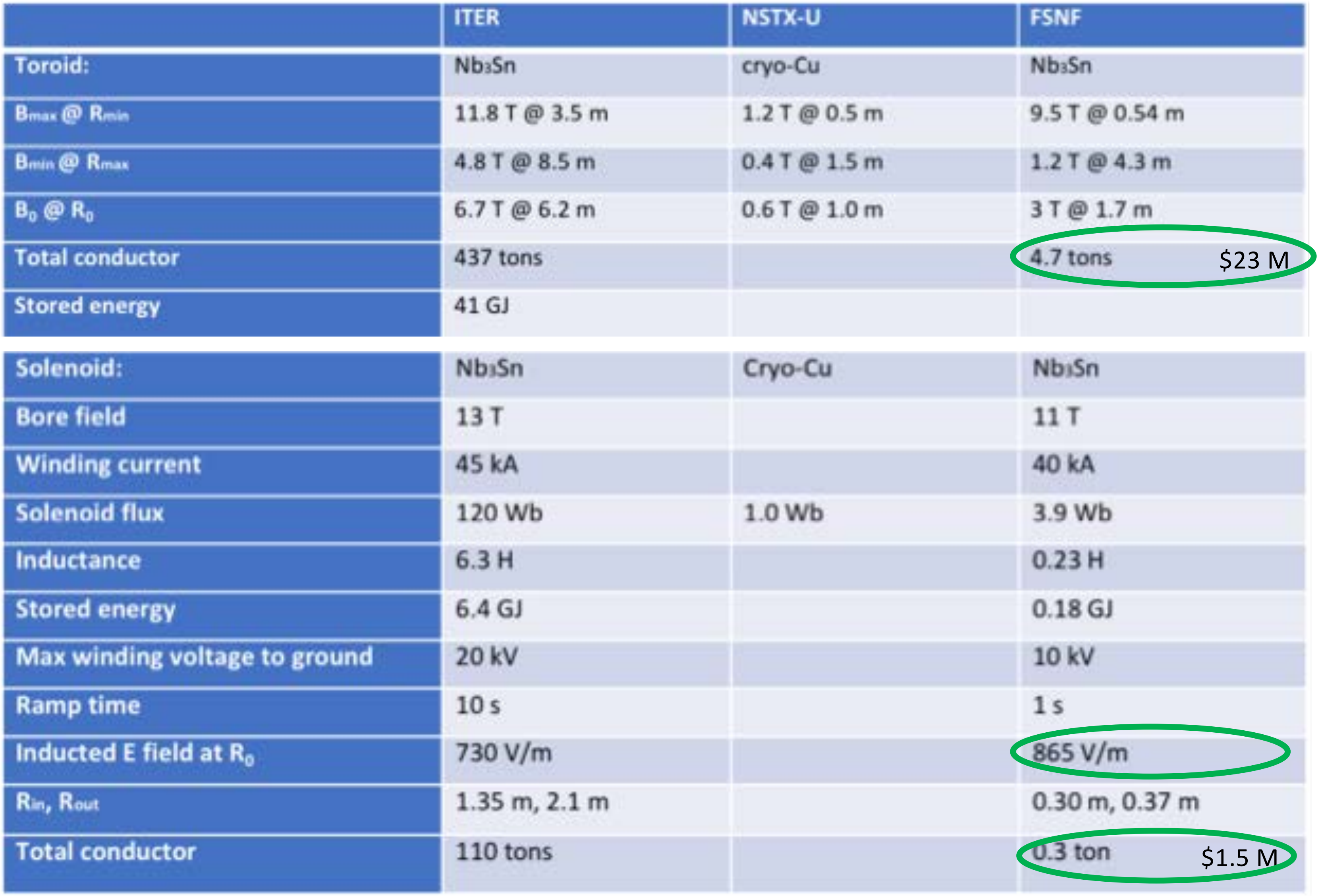
Applying SuperCIC for the toroid and dipole of FNSF yields some nice enhancements



- An 11 T Nb_3Sn solenoid that takes only 8 cm of radial space, lives within the small hole in the ST, yet produces 4 Wb of fast-ramp flux.
- Or a 26 T hybrid solenoid that takes 16 cm of radial space and produces 8 Wb of flux.

- A 3 T (@R_0 = 1.7 m) toroid that locates 50 turns of SuperCIC in 4 layers, again with ~8 cm of radial space. Stress management is handled largely within each D-winding, so that a maximum of space is available for poloidal windings and mid-plane access ports.

Now compare parameters of ITER and ST-FNSF using SuperCIC



	ITER	NSTX-U	FSNF
Toroid:	Nb_3Sn	cryo-Cu	Nb_3Sn
B_{max} @ R_{min}	11.8 T @ 3.5 m	1.2 T @ 0.5 m	9.5 T @ 0.54 m
B_{min} @ R_{max}	4.8 T @ 8.5 m	0.4 T @ 1.5 m	1.2 T @ 4.3 m
B_0 @ R_0	6.7 T @ 6.2 m	0.6 T @ 1.0 m	3 T @ 1.7 m
Total conductor	437 tons		4.7 tons $23 M
Stored energy	41 GJ		

Solenoid:	Nb_3Sn	Cryo-Cu	Nb_3Sn
Bore field	13 T		11 T
Winding current	45 kA		40 kA
Solenoid flux	120 Wb	1.0 Wb	3.9 Wb
Inductance	6.3 H		0.23 H
Stored energy	6.4 GJ		0.18 GJ
Max winding voltage to ground	20 kV		10 kV
Ramp time	10 s		1 s
Inducted E field at R_0	730 V/m		865 V/m
R_{in}, R_{out}	1.35 m, 2.1 m		0.30 m, 0.37 m
Total conductor	110 tons		0.3 ton $1.5 M

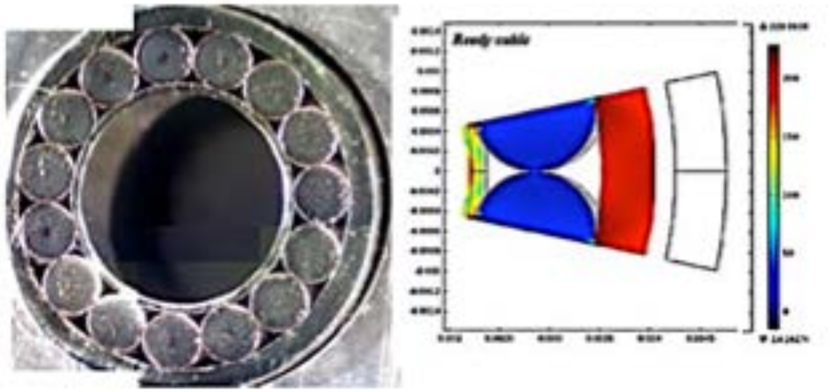
The SuperCIC solenoid has the same induced E at the plasma as does CS in ITER.

Details for the three FNSF options:

Toroid:				
R0	1	1.7	3	m, center of plasma region
B @ R0	3	3	4.1	T
Bmax coil	9.1	9.5	13.7	T
N	10	12	20	Sectors
Isector	1.5	2.1	3.1	MA
Icab	41.7	39.4	42.7	kA
d_{cic}	0.011	0.011	0.011	m
CiC with armor (square)	0.014	0.014	0.014	m
Structure stress	308	311	307	MPa
Strand Stress	200	202	200	MPa
Solenoid:				
Icab	50	40	40	kA
B center	8.7	11.0	12.7	T
CiC with armor (square)	0.014	0.018	0.020	m
Layers	2	4	5	
Rout	0.23	0.37	0.41	m
Rin	0.20	0.30	0.31	m
Ftension	95	296	461	kN
Armor stress	306	310	307	MPa
strand stress	199	201	200	MPa

The ultimate benefits of our SuperCIC for high-field windings come from four innovations

1. Support the wires in a layered structure that spring-loads the wires against the sheath, so that they are immobilized yet cannot be crushed by small deformations in the sheath:



2. Lock the twist pitch *L* of the wires so that each wire traverses an integer number of twists around each bend of the cable: $\pi R = NL$. Thus all wires traverse the same catenary length around the bend and no tension or compression is created in the neighboring regions of the winding.

3. Form a 2-segment armor shell around the CIC, formed and installed on the CIC during winding *without welding*. Two candidates for the material for the armor shell are Inconel 908 and Ti-6Al-4V.

   Ti-6Al-4V can be extruded in final-shape appropriate for the 2-segment armor with remarkably modest cost. Studies of cryogenic fatigue show that titanium can be extremely robust.

4. Wind solenoid in a barrel-wind configuration rather than pancakes. The successive radial segments can then be graded in wire composition (wire diameter or Cu:SC ratio), or even in superconductor (Nb3Sn outer shell, Bi-2212 inner shell) so that all layers utilize conductor to the same fraction of I_c:

   The accumulating Lorentz stress in the armor can also be terminated at an over-band on each shell, as with NMR.

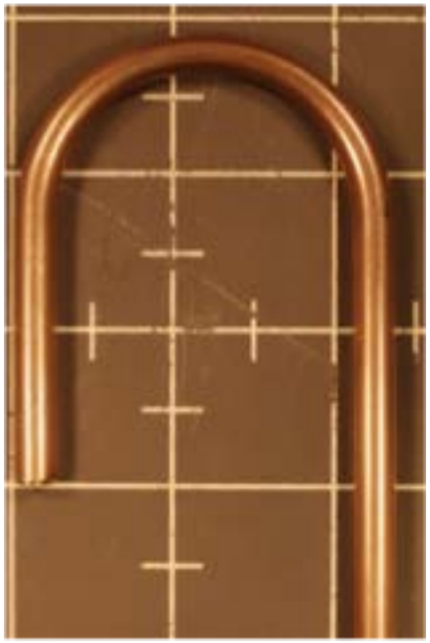
ARL has transferred SuperCIC technology to two companies:

Accelerator Technology Corp. (College Station, TX)

HyperTech (Columbus, OH)

ATC and HyperTech are manufacturing 125 m lengths of SuperCIC today.

ARL has the process equipment to fabricate windings and do heat treatments for Nb_3Sn and Bi-2212



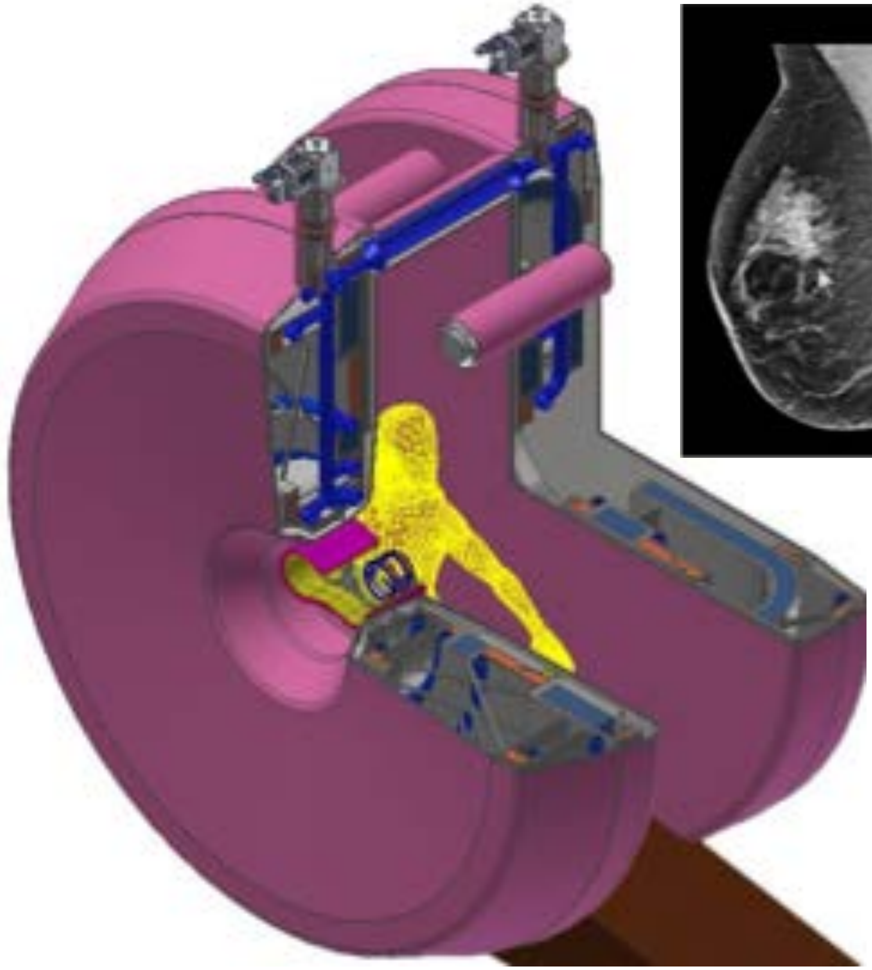
Zoned stack furnace (extendable to 4 m)

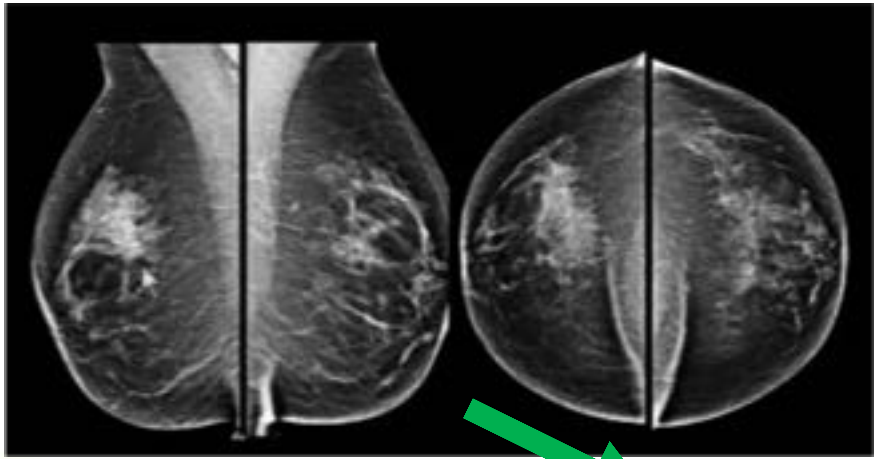
Sheath tube can serve as pressure retort for 50 atm overpressure processing of Bi-2212 windings.

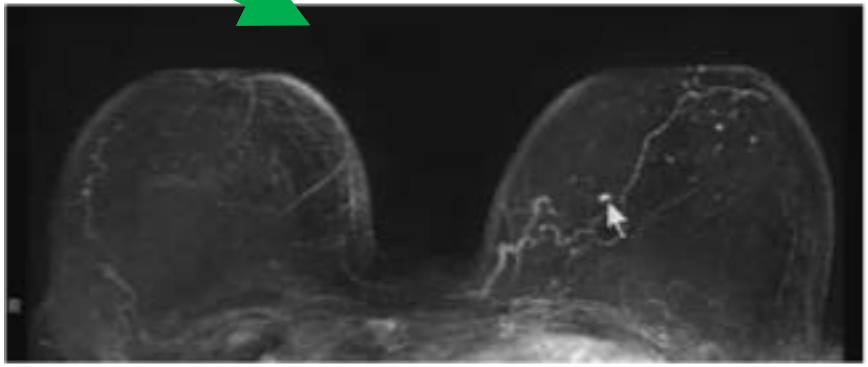
ARL has a track record of innovation to apply magnetics to difficult challenges.

An example that has some echoes to the challenges for poloidal windings:

1.5 Tesla OpenMR Scanner for Well-patient screening - Early detection of breast cancer

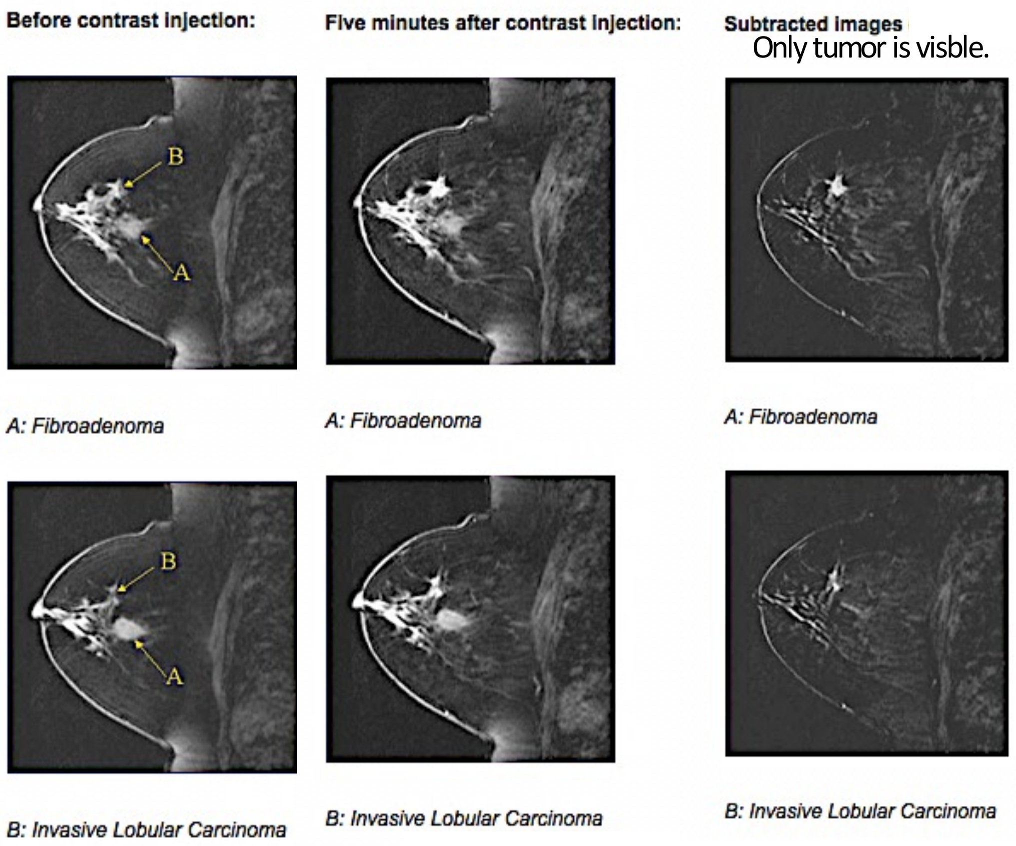






Dynamic MRI of the Breast

Dynamic MRI detects tumors via the uptake of sugar (DPTA) containing Gd contrast agent. A pre-injection image is take , the dye is injected into the bloodstream. It concentrates in the new vasculature in the tumor tissue. Images are taken at one-second intervals to produce a high-contrast identification.



Before contrast injection:

Five minutes after contrast injection:

Subtracted images
Only tumor is visble.

A: Fibroadenoma

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B: Invasive Lobular Carcinoma

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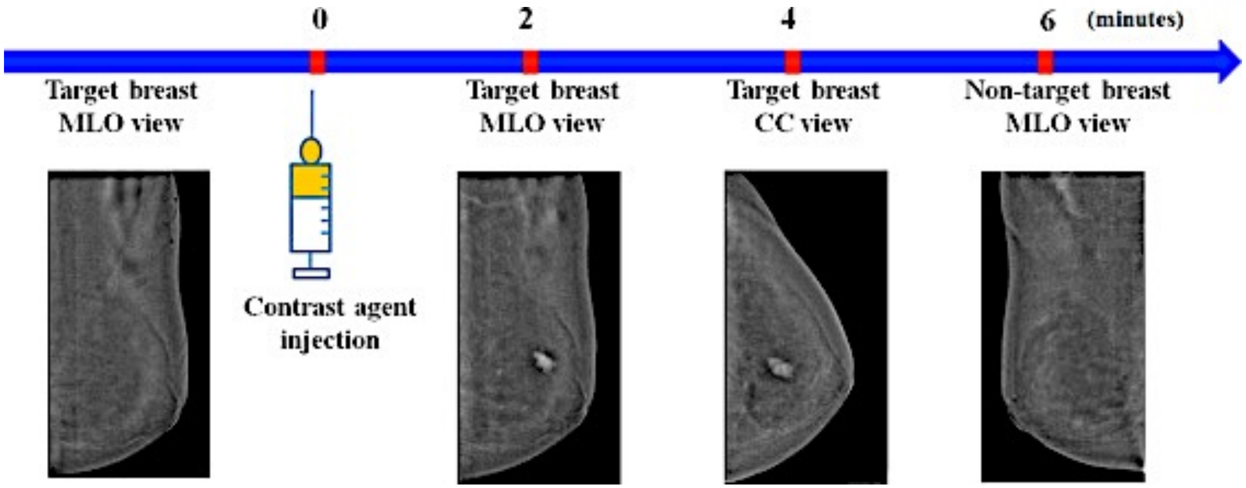
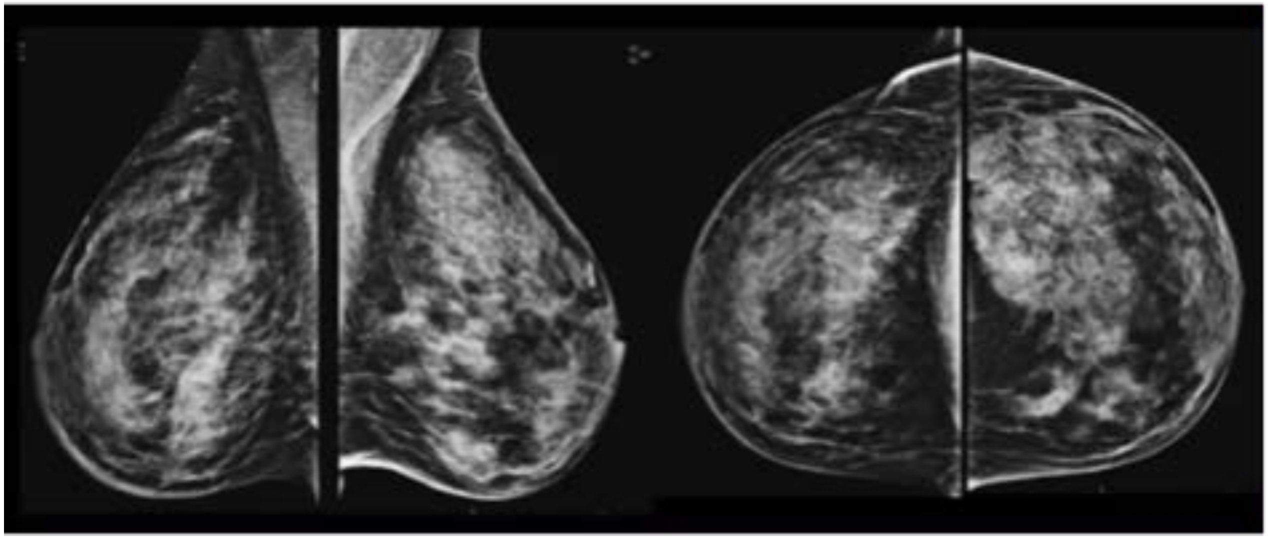
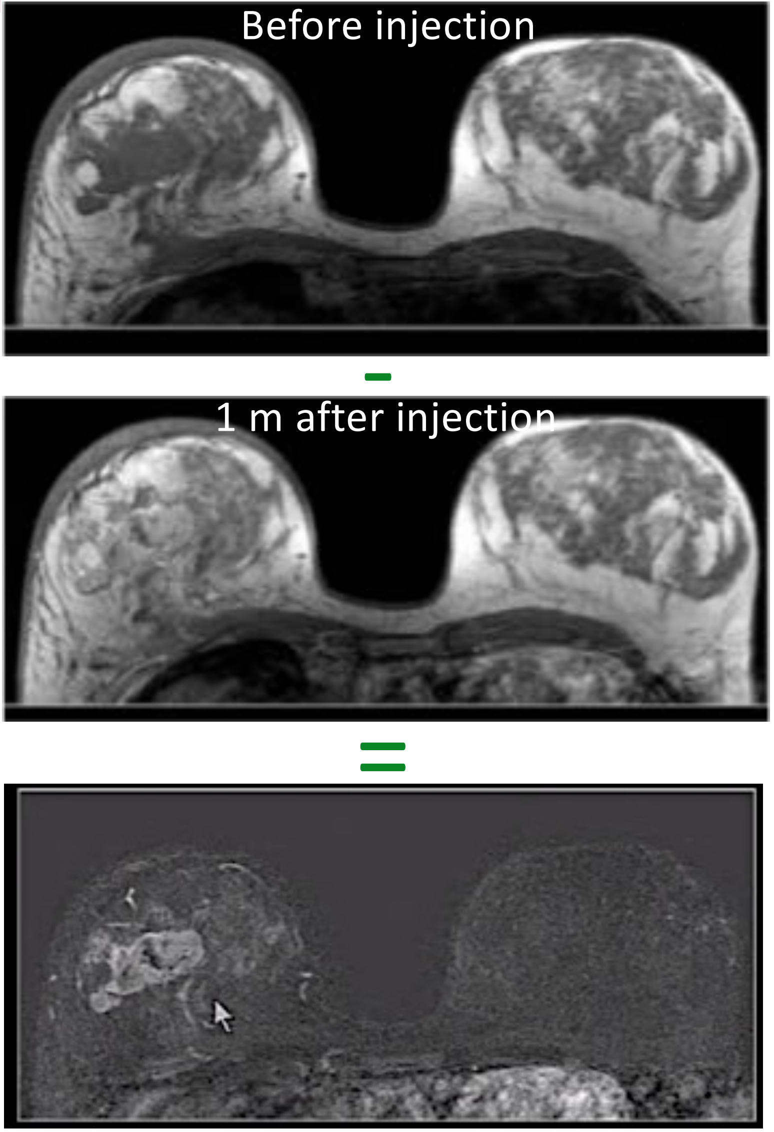


1. MRI imaging of the breast has matured to provide superior performance for early detection of breast cancer, compared with mammography or ultrasound. Let’s first look at images:

A patient comes in with a palpable lump.

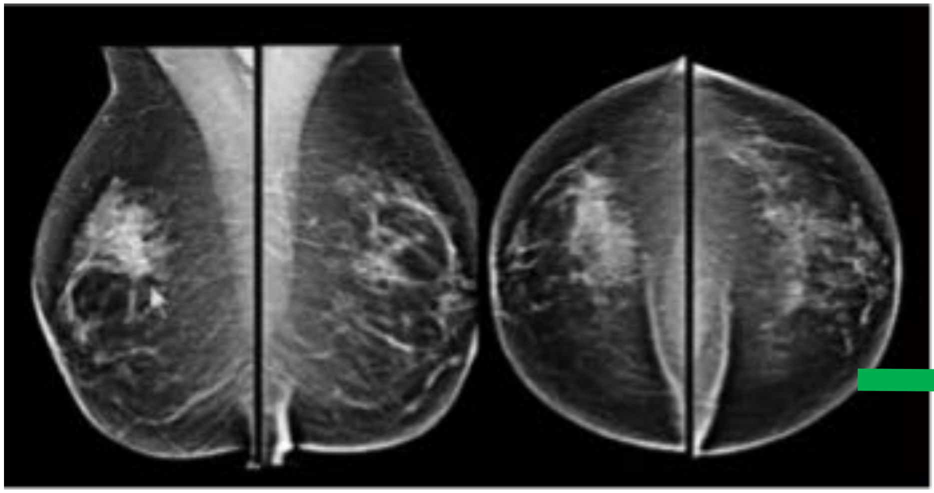


Mammogram: Is there cancer? If so, where?

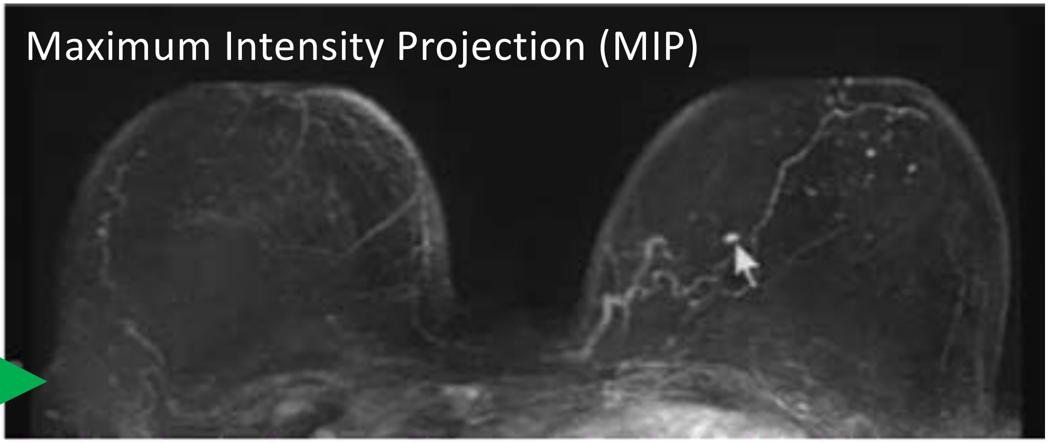


Dynamic MRI: 8 cm invasive tumor

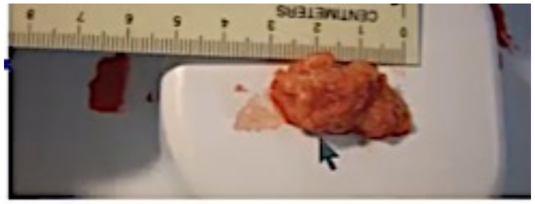
A 50-year-old patient comes for her first mammogram.

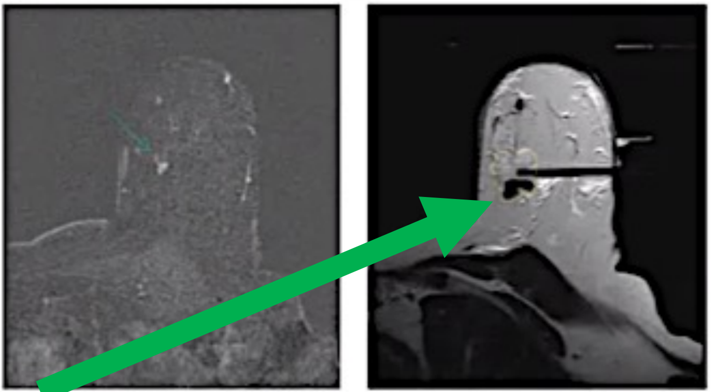


Mammogram: Large mass apparent in right breast, is it simply asymmetric involution of a healthy breast, or is it diffusively infiltrating lobular cancer in the fibro-glandular tissue?

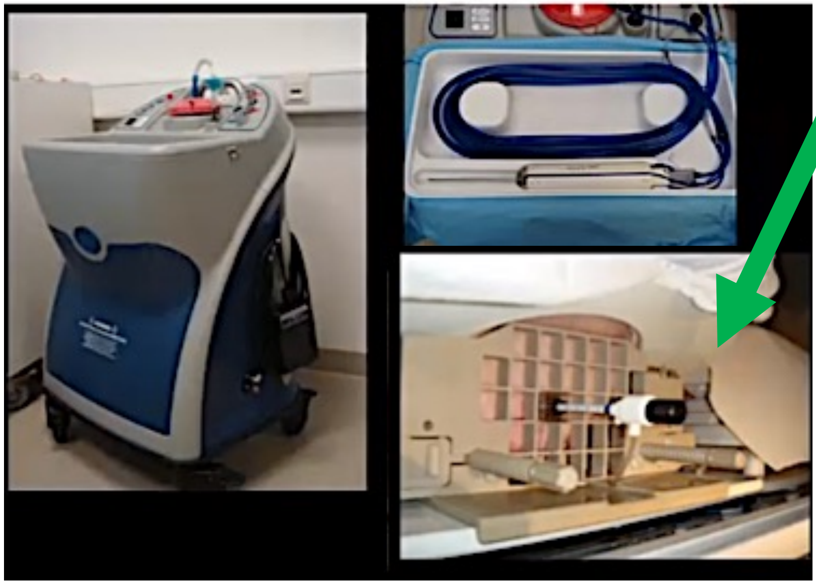


Dynamic MRI: The right breast is completely normal, but there is a ~4 mm invasive tumor in the left breast (invisible on the mammogram).



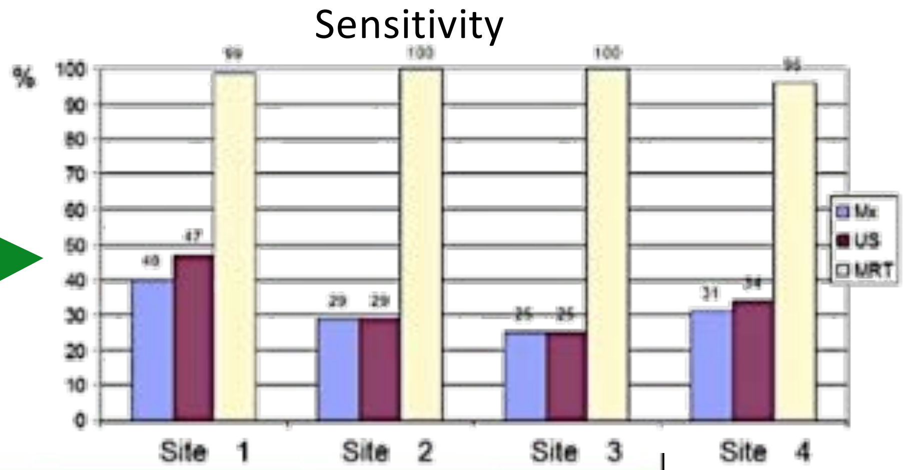


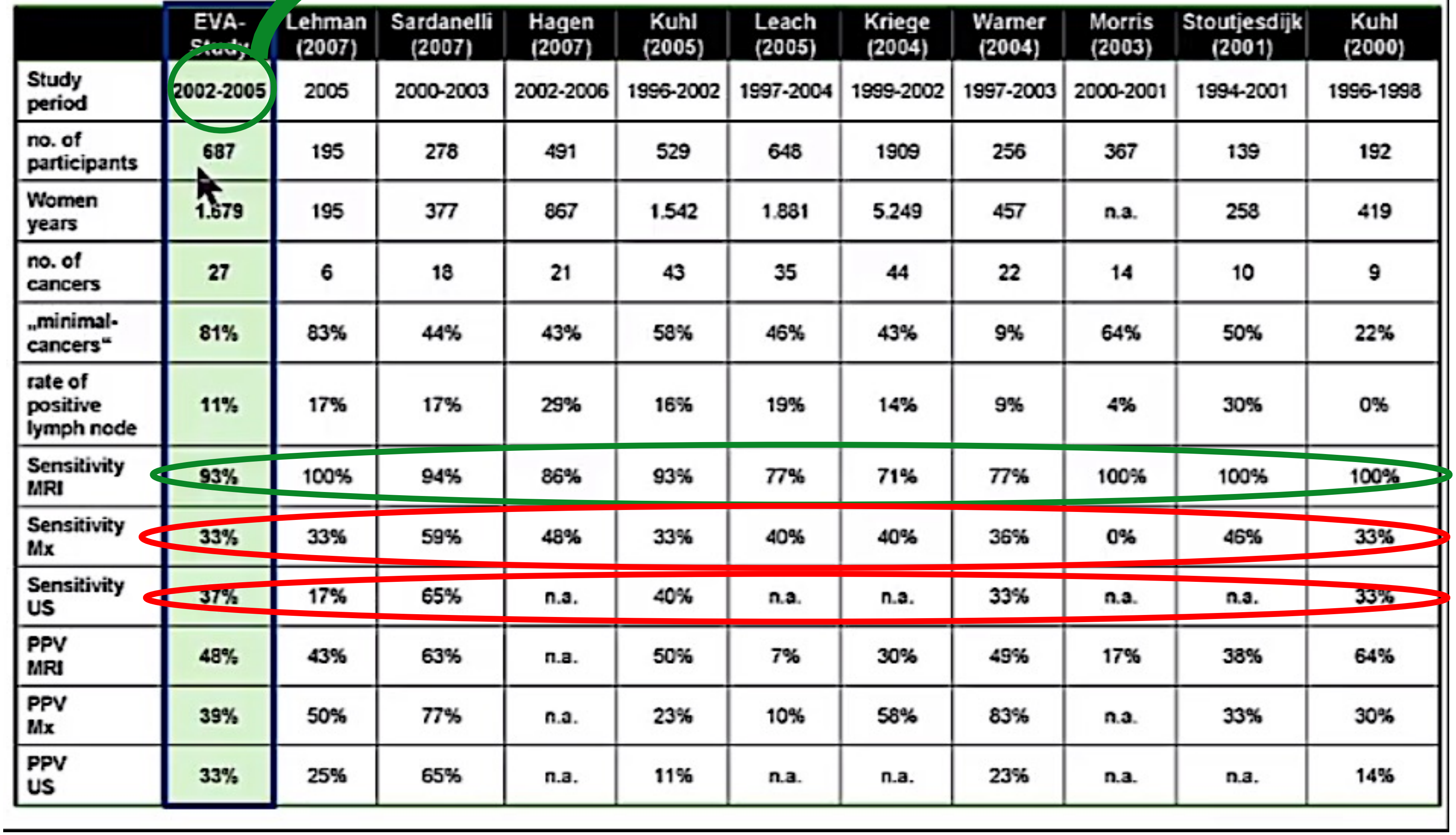
Pathology and subsequent MRI show that the entire tumor was removed.



MR-guided vacuum biopsy of the suspect tissue: MR guidance vital to precisely resect the right 4 mm spot.

Now look at the data:

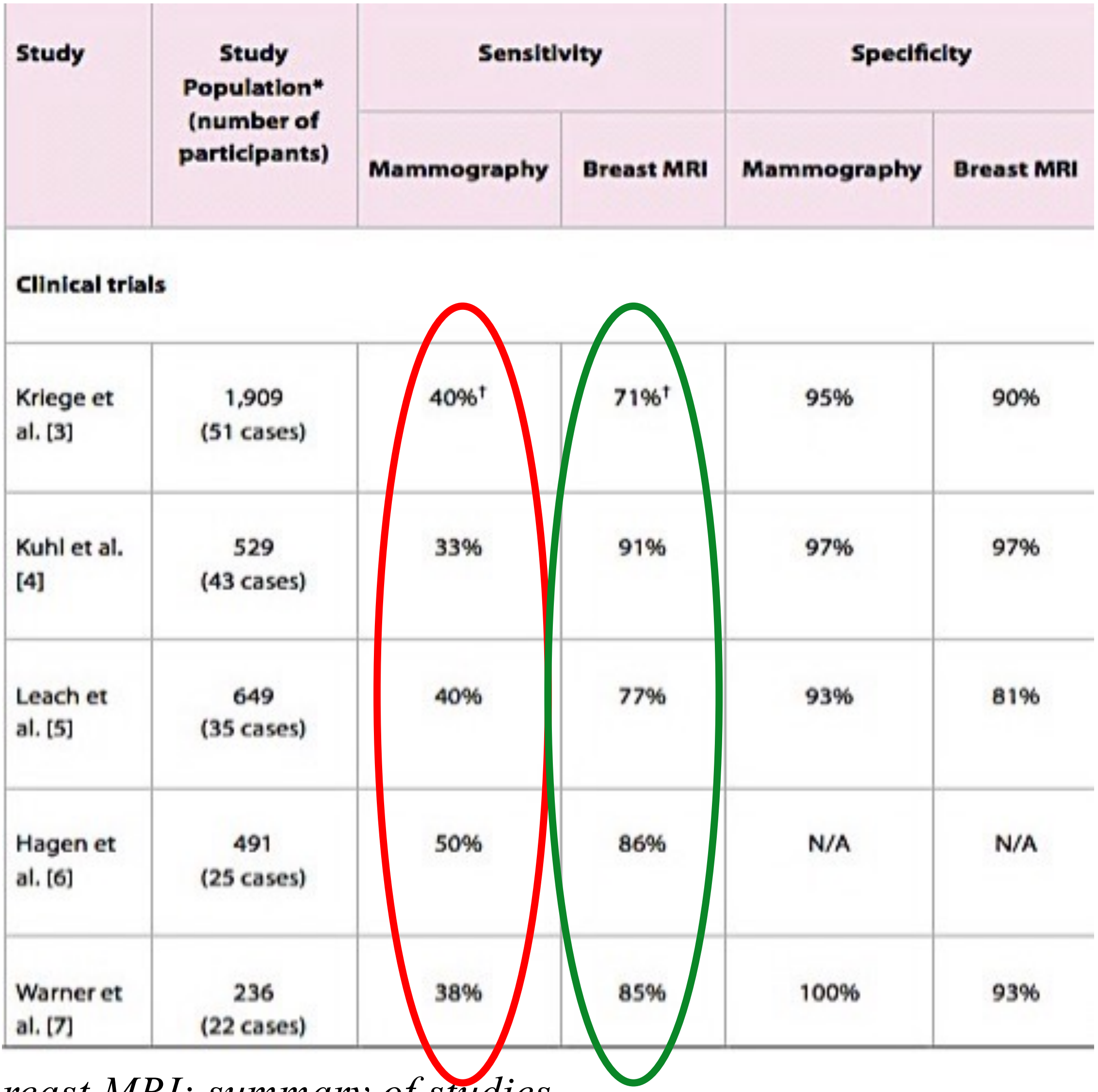




	EVA-Study	Lehman (2007)	Sardanelli (2007)	Hagen (2007)	Kuhl (2005)	Leach (2005)	Kriege (2004)	Warner (2004)	Morris (2003)	Stoutjesdijk (2001)	Kuhl (2000)
Study period	2002-2005	2005	2000-2003	2002-2006	1996-2002	1997-2004	1999-2002	1997-2003	2000-2001	1994-2001	1996-1998
no. of participants	687	195	278	491	529	648	1909	256	367	139	192
Women years	1.679	195	377	867	1.542	1.881	5.249	457	n.a.	258	419
no. of cancers	27	6	18	21	43	35	44	22	14	10	9
„minimal-cancers"	81%	83%	44%	43%	58%	46%	43%	9%	64%	50%	22%
rate of positive lymph node	11%	17%	17%	29%	16%	19%	14%	9%	4%	30%	0%
Sensitivity MRI	93%	100%	94%	86%	93%	77%	71%	77%	100%	100%	100%
Sensitivity Mx	33%	33%	59%	48%	33%	40%	40%	36%	0%	46%	33%
Sensitivity US	37%	17%	65%	n.a.	40%	n.a.	n.a.	33%	n.a.	n.a.	33%
PPV MRI	48%	43%	63%	n.a.	50%	7%	30%	49%	17%	38%	64%
PPV Mx	39%	50%	77%	n.a.	23%	10%	58%	83%	n.a.	33%	30%
PPV US	33%	25%	65%	n.a.	11%	n.a.	n.a.	23%	n.a.	n.a.	14%

Dynamic MRI has ~twice the sensitivity for early detection of breast cancer compared to mammogram.

While the sensitivity of mammography is improving with the advent of 3D mammography, so the sensitivity of CBMRI is improving with advanced protocols.



Study	**Study Population* (number of participants)**	**Sensitivity**		**Specificity**	
		Mammography	**Breast MRI**	**Mammography**	**Breast MRI**
Clinical trials					
Kriege et al. [3]	1,909 (51 cases)	40%†	71%†	95%	90%
Kuhl et al. [4]	529 (43 cases)	33%	91%	97%	97%
Leach et al. [5]	649 (35 cases)	40%	77%	93%	81%
Hagen et al. [6]	491 (25 cases)	50%	86%	N/A	N/A
Warner et al. [7]	236 (22 cases)	38%	85%	100%	93%

Sensitivity and specificity of mammography and breast MRI: summary of studies.
[https://ww5.komen.org/BreastCancer/Table32MRIplusmammographyversusmammographyaloneinhigh riskwomen.html](https://ww5.komen.org/BreastCancer/Table32MRIplusmammographyversusmammographyaloneinhighriskwomen.html)

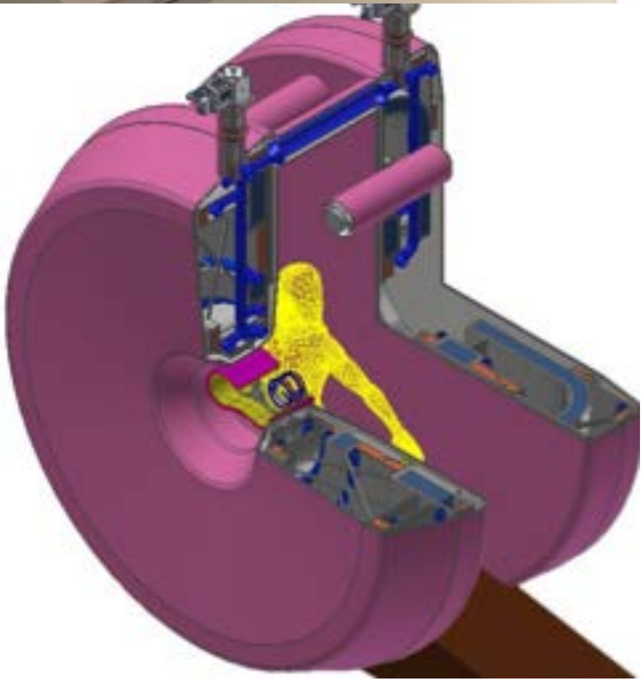
But Dynamic MRI is not affordable for well-patient screening!

The excellent performance of Dynamic MRI we have just seen was achieved in whole-body MRI systems.

Unfortunately those systems cost ~$1.5 million, it takes ~1 hour to image one patient, so the images cost $1,000.

That cost is not affordable for well-patient screening.

But the potential to save lives of women whose cancer is missed in mammography can only be realized in well-patient screening.

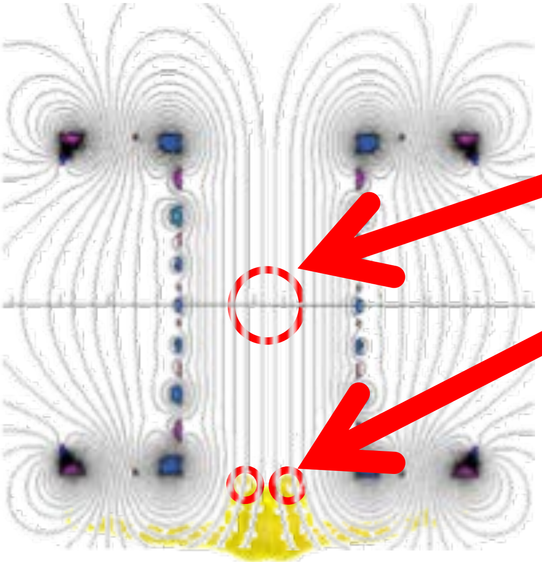


We set out to develop a walk-through OpenMR Breast Imager that can achieve the same image quality as a whole-body MR imager, and process 6 patients per hour.

Time is money: the OpenMR Breast Imager can produce screening images for $377/image – the same cost as 3D mammography.

The goal is not to make dynamic MRI better – it is to make it less expensive with the same excellent performance so that it can be reimbursable for well-patient screening.

Challenge for Magnetics: make a homogeneous field *outside the magnet*



A whole-body MRI scanner produces a ~homogeneous field in its center by extending the body long enough

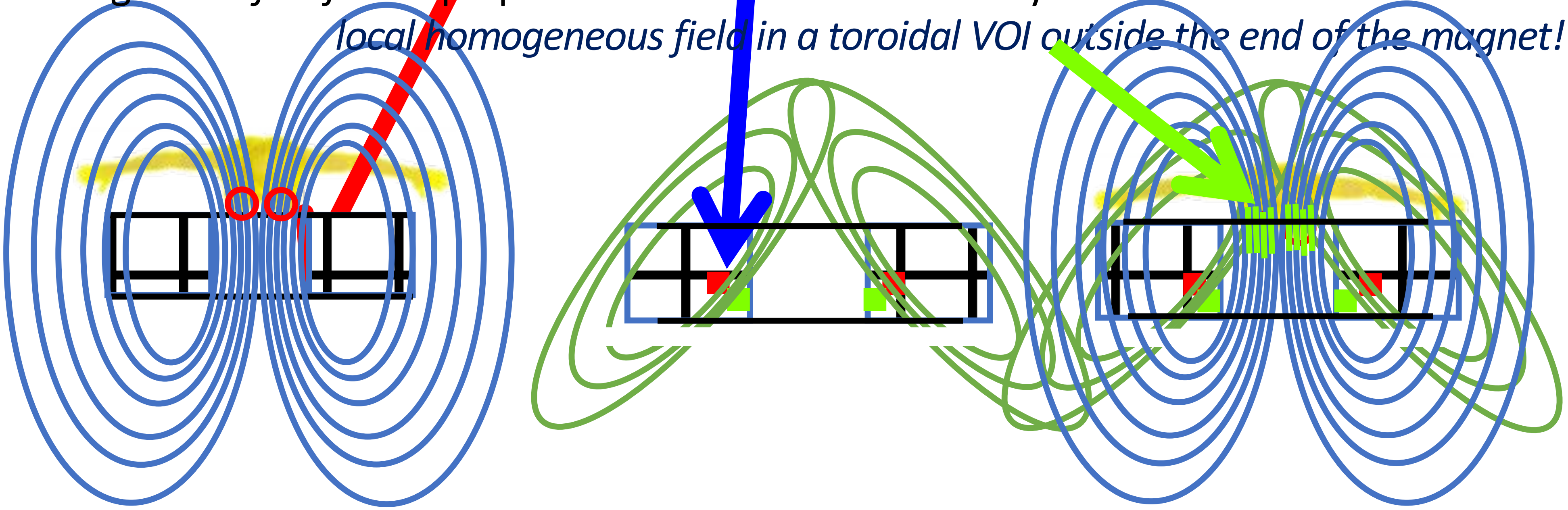
- *expensive, claustrophobic, and the patient is inaccessible*.

The field distribution in the end region strongly diverges, *so you cannot do MRI in the end region of a solenoid.*

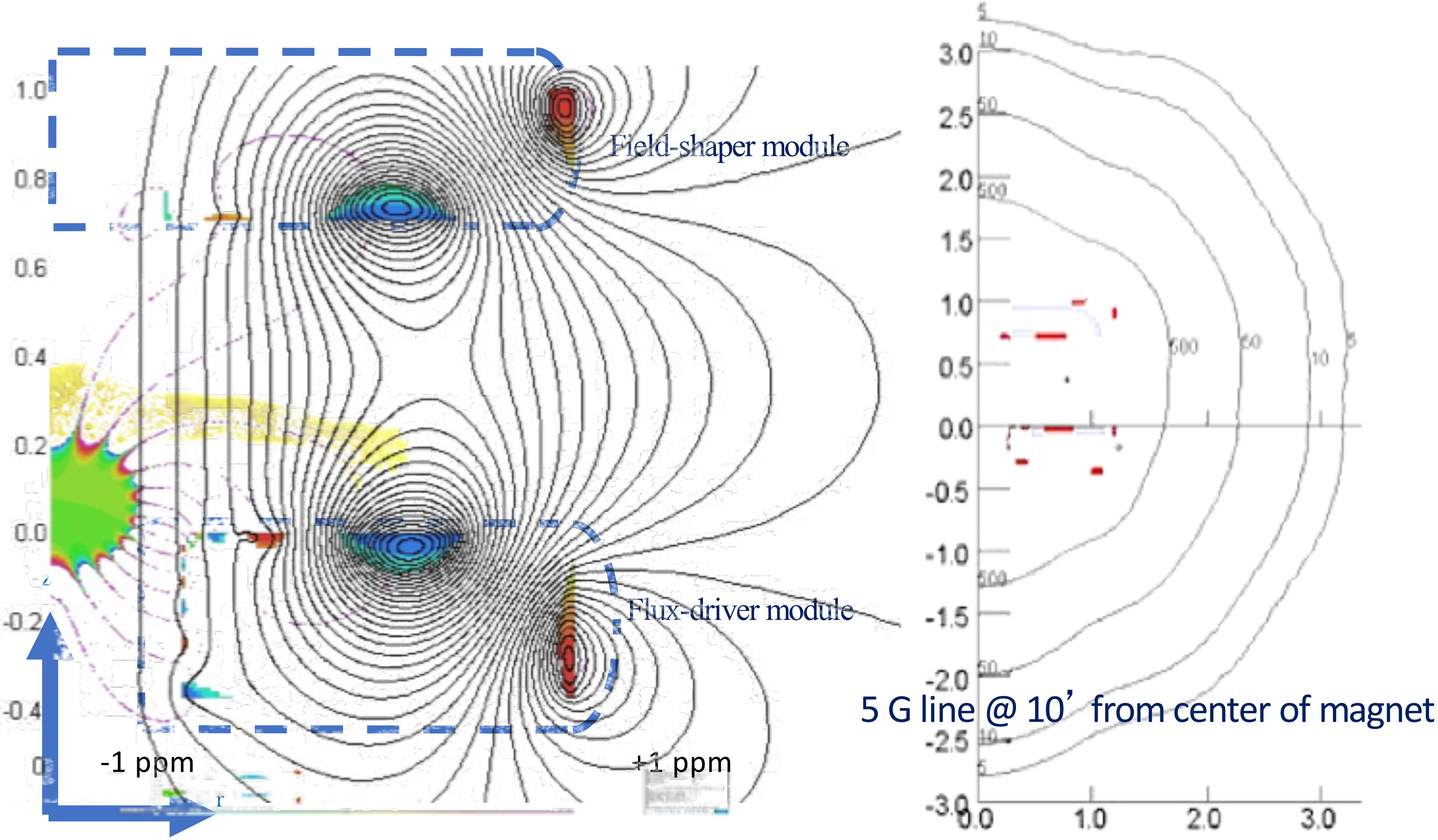
Now make a *structured coil*, in which the current in each element is an independent variable. You can adjust the currents however, but *you can’t get homogeneous field in the end region*.

Now put *opposing currents* in diagonal pairs of elements. It produces *converging field* in an end region – *a flux jet*. Superpose the two distributions and you can make

local homogeneous field in a toroidal VOI outside the end of the magnet!



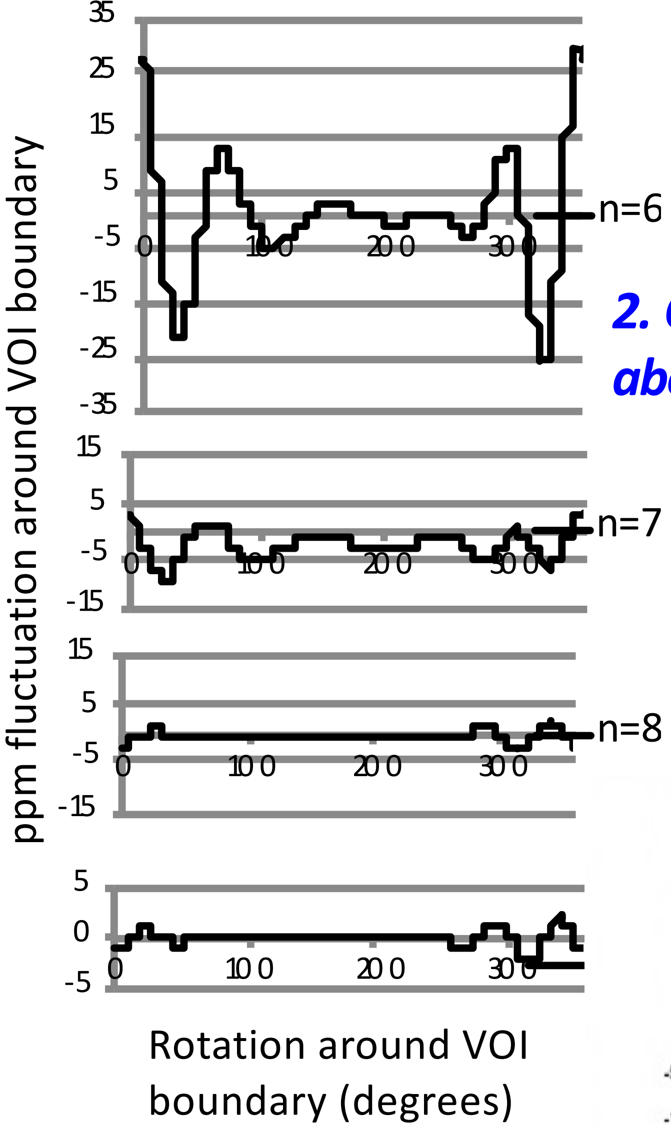
Magnetic fields you can walk into for an image



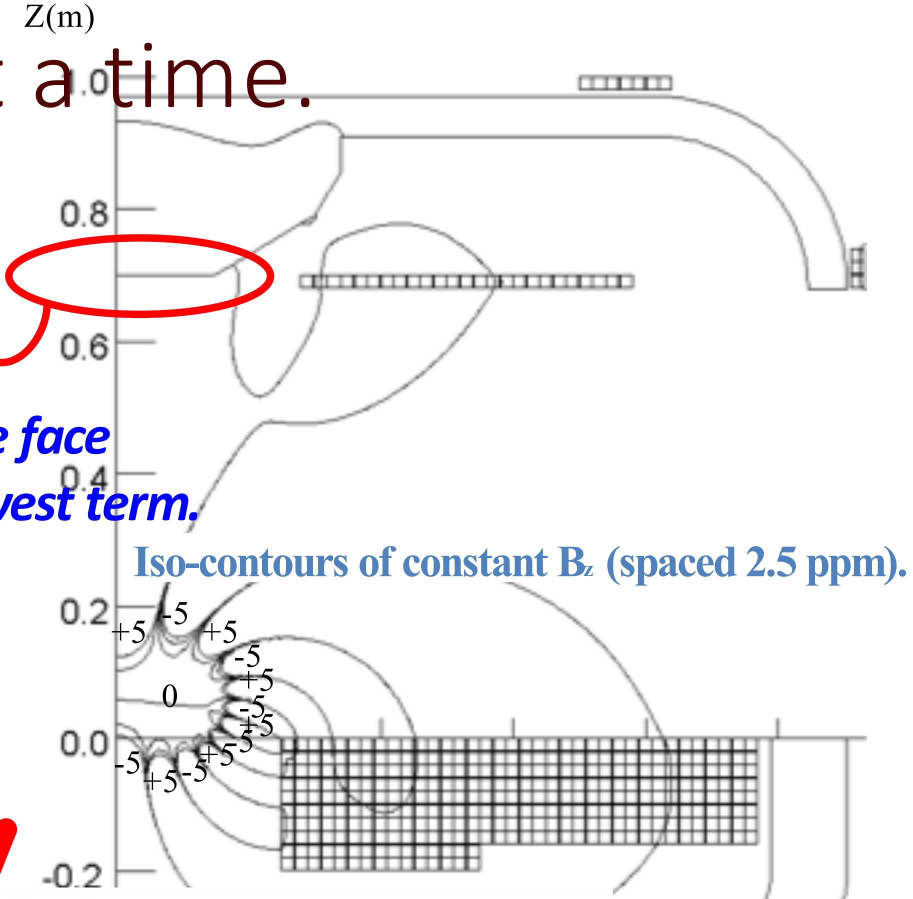
5 G line @ 10’ from center of magnet

This is a slice through the horizontal mid-plane of the OpenMR Breast Imager.
There are 15 windings: 9 have clockwise current (red), 6 have counterclockwise current (blue).
The green region is the toroidal imaging field: 1.5 Tesla with <ppm variation over the breast.

Kill multipoles, one order at a time.

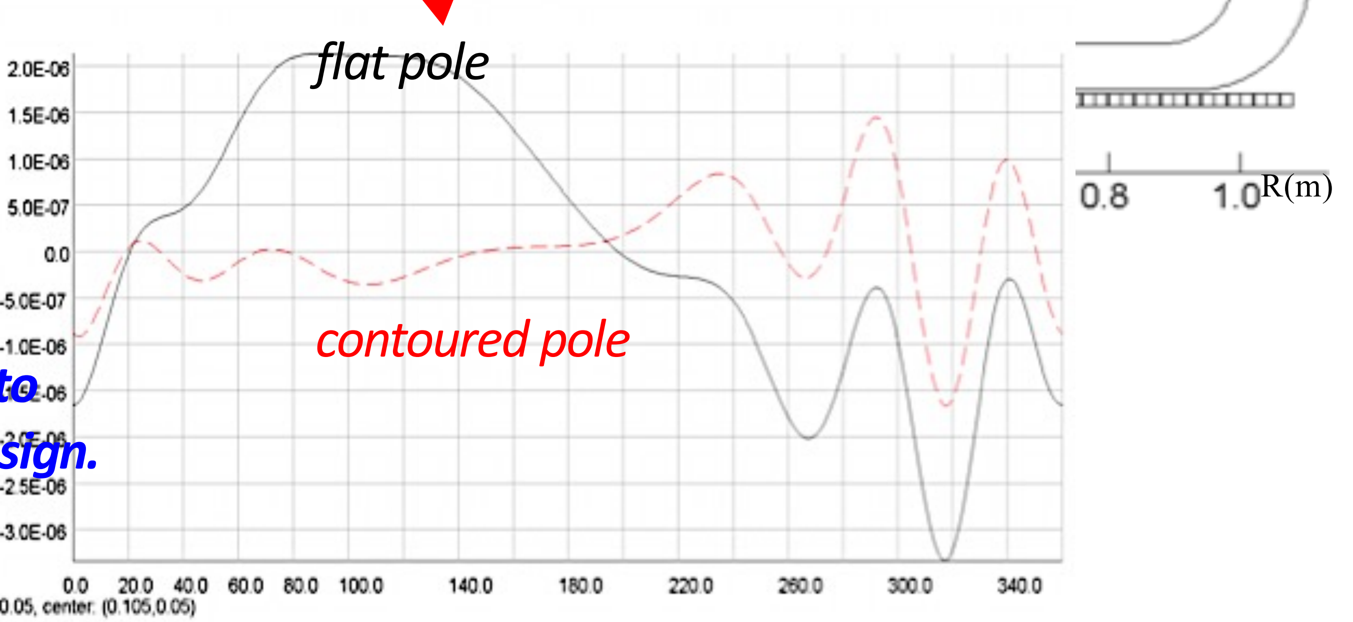


1. ***Diagonalize current matrix to kill each multipole in the design.***



2. ***Contour the steel pole face above the VOI to kill lowest term.***

Iso-contours of constant B_z (spaced 2.5 ppm).



ARL, ATC, HyperTech offer collaboration to develop magnetics that can enable the maximum potential for ST-FNSF

We know particle accelerators, we have pioneered cable, coil, and magnet technologies that extend their performance and reduce their cost.

We have no experience with plasmas or tokomaks, but the magnetics challenges appear to have much in common with the world of accelerators.

I have shown examples of our what we have done:

- SuperCIC cable that preserves the full performance of high-field superconductors;
- Coil technology to optimize stress management and preserve the full strength of super-alloy armor;
- Hybrid winding technology to use each part of the windings to the same fraction of Ic;
- Demountable joint technology to interconnect windings;
- Magnetic design methods that use flux jets to optimize desired field distributions.