Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

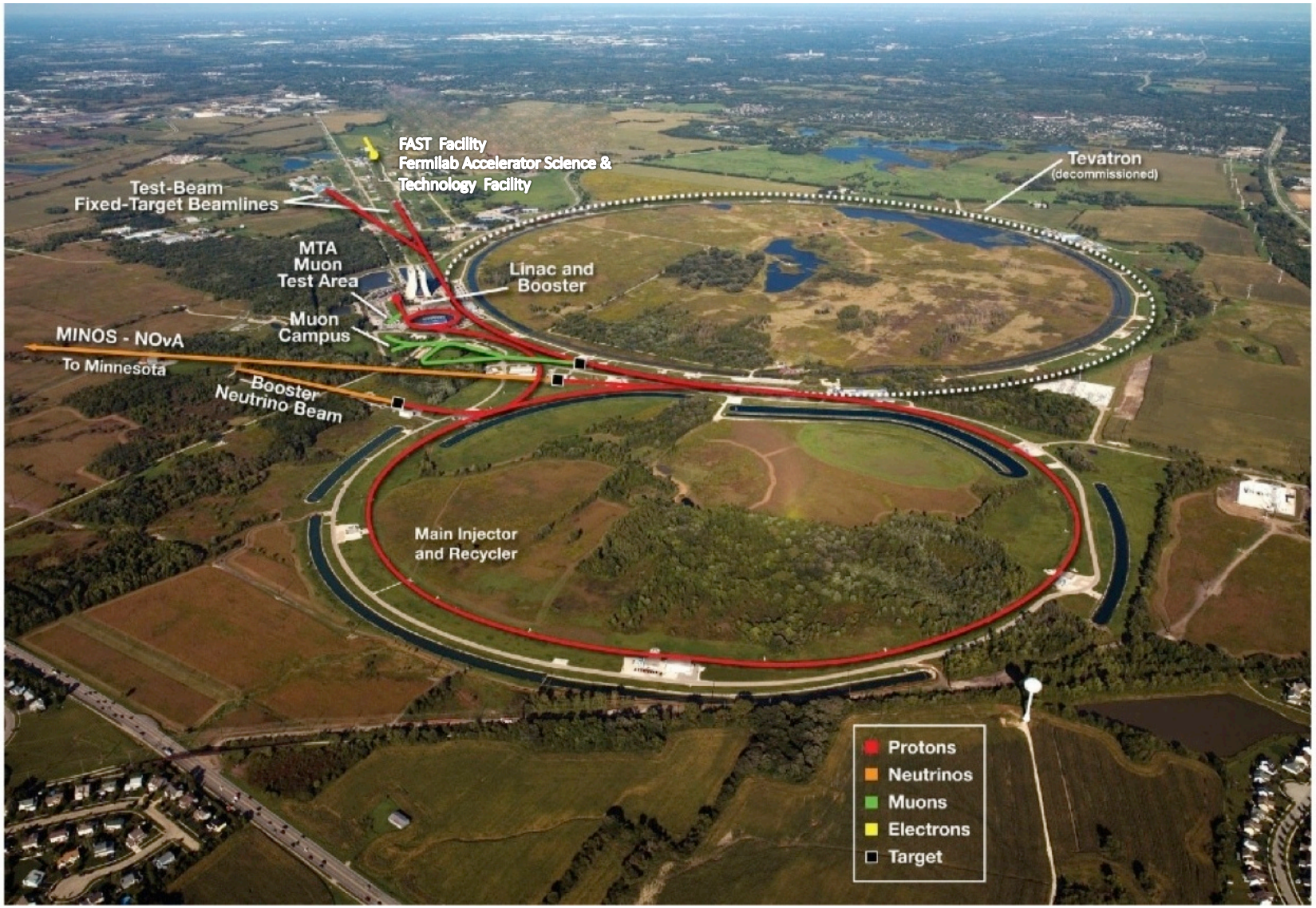
Mechanical Engineering of Accelerators

Linda Valerio

Undergraduate Lecture Series

23 June 2016

Introductions – Fermilab accelerator complex



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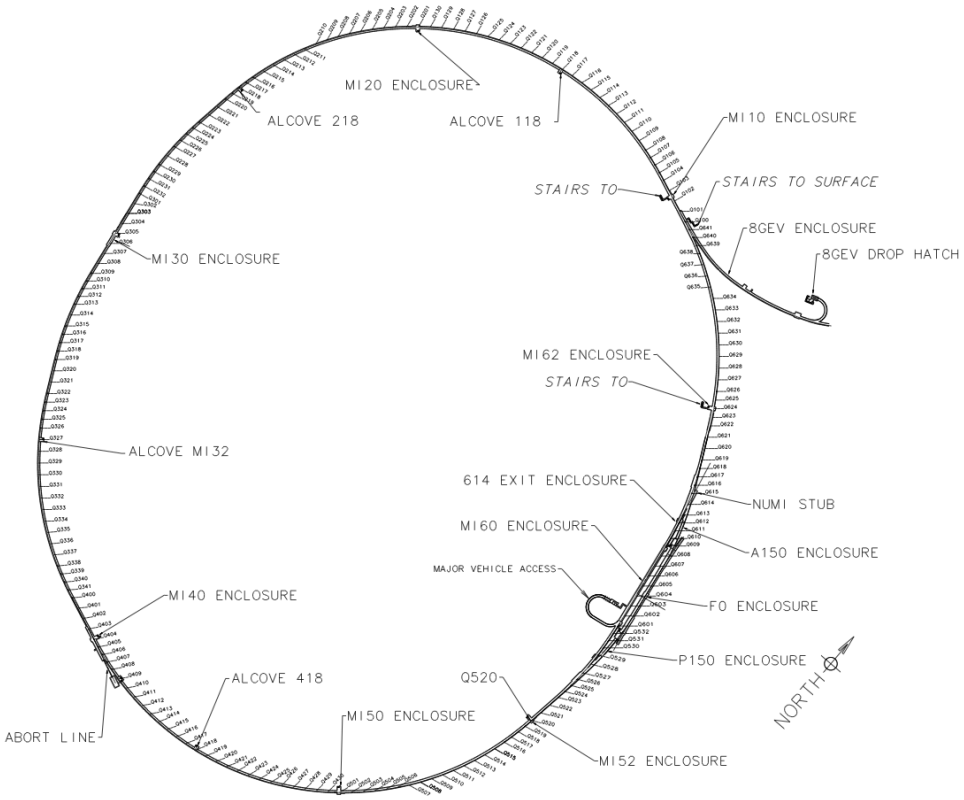
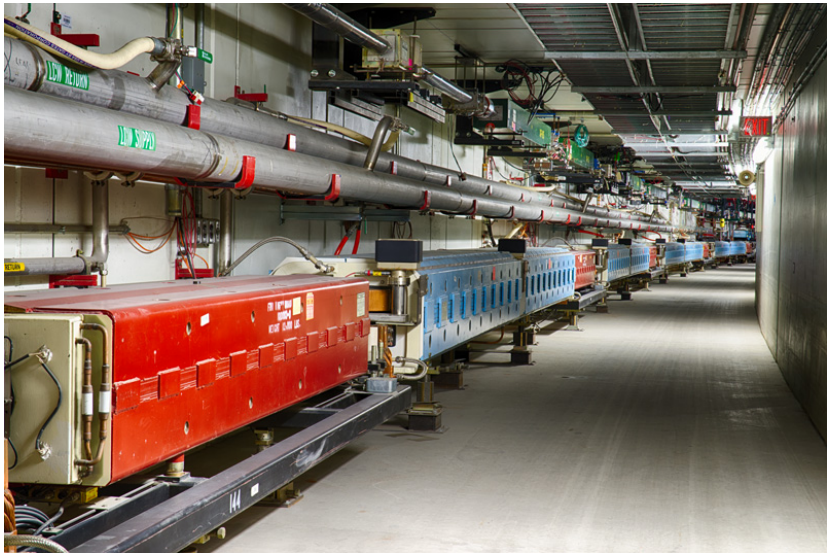
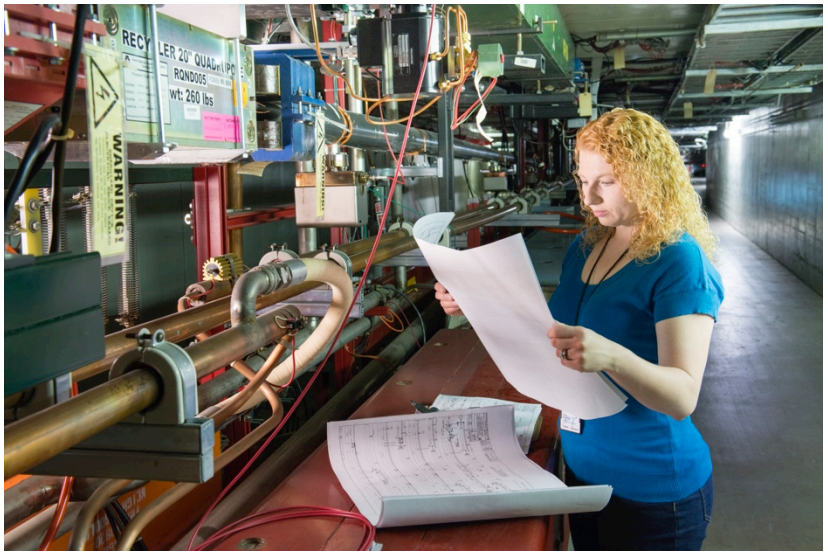
Introductions – Main Injector







photos by R. Hahn

1999 – construction complete

2011 – central machine (Tevatron retired)

2 miles in circumference

208 quadrupole magnets

344 dipole magnets

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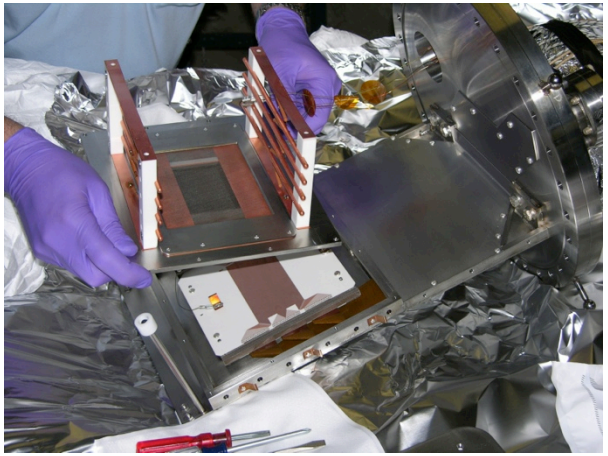
Examples of engineering in the MI enclosure

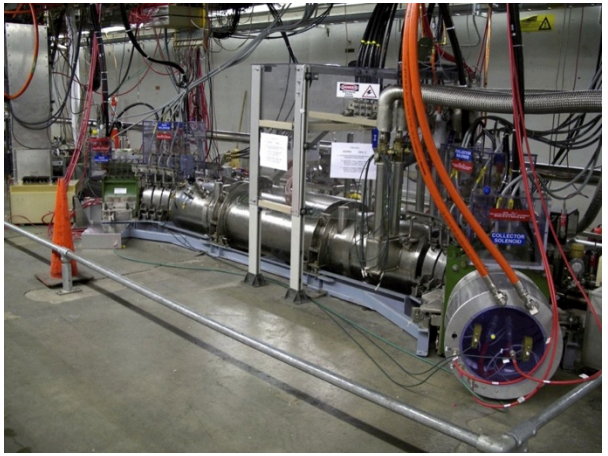
Civil

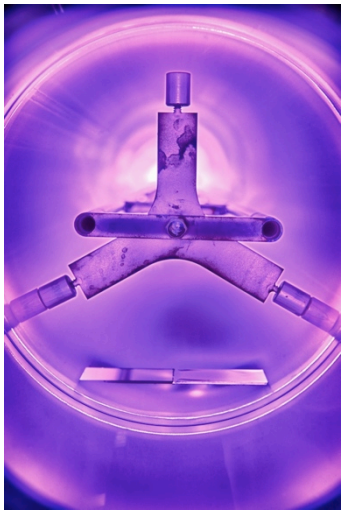
Mechanical

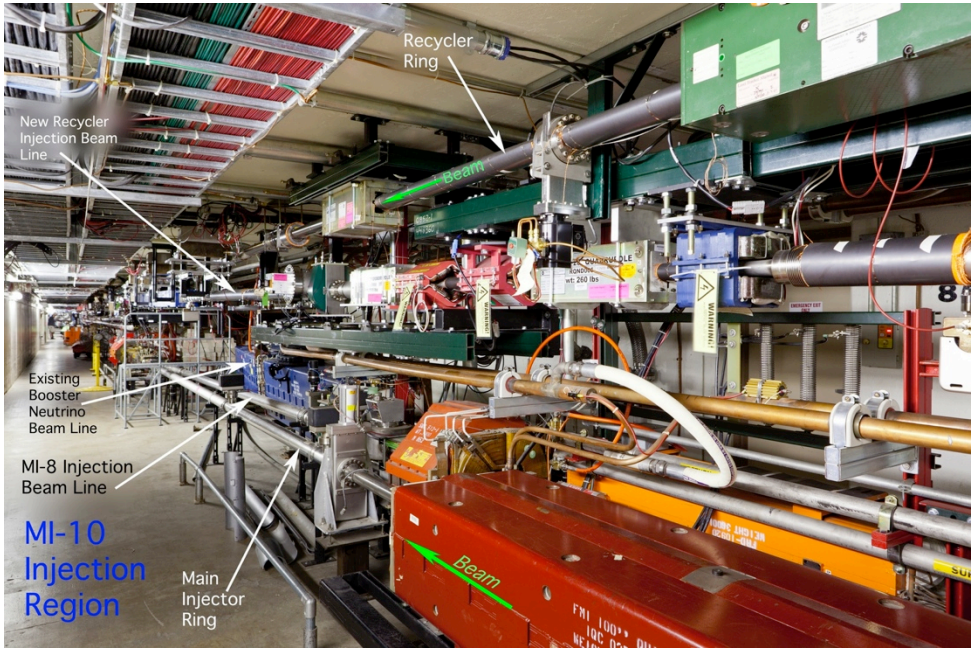
Electrical

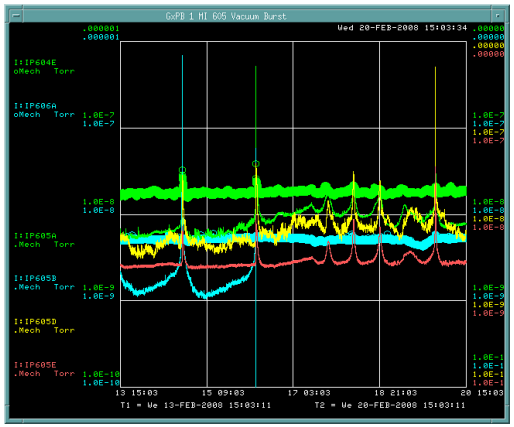
Accelerator engineering at Fermilab











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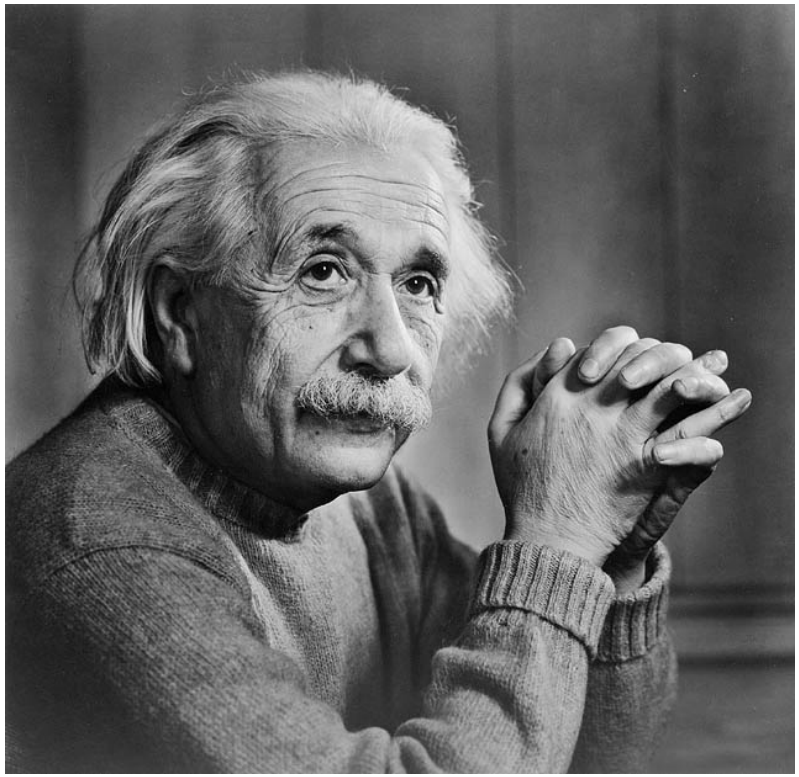
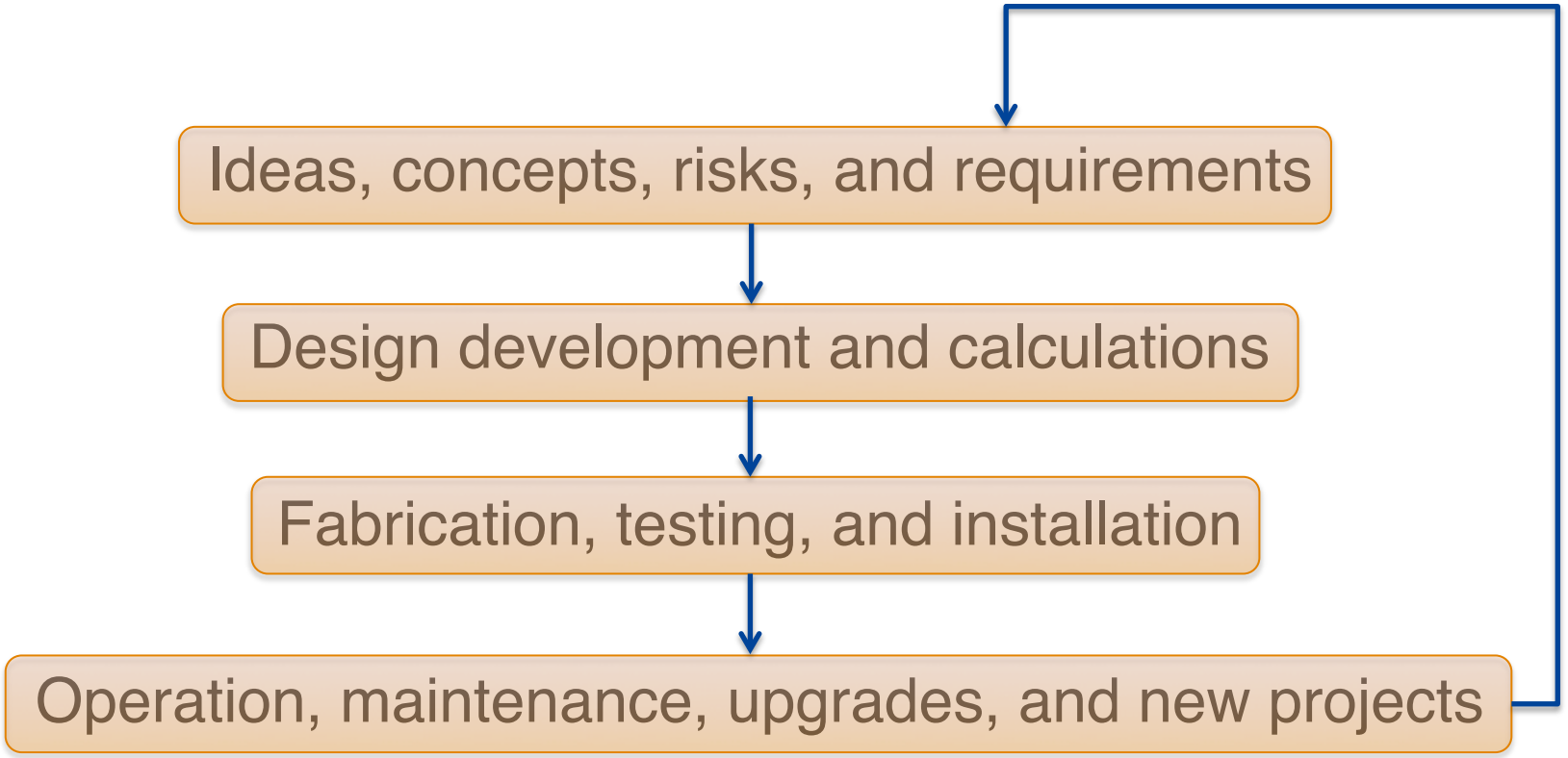
How is an engineer different from a scientist?

"Scientists investigate that which already is;
Engineers create that which has never been."
- Albert Einstein



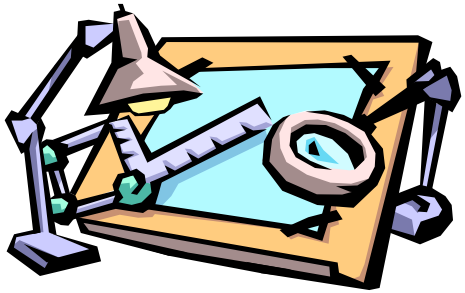
Engineering process



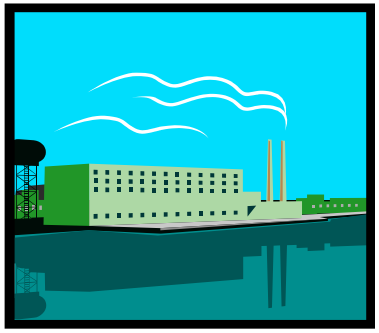
Further reference: Fermilab Engineering Manual available online

Typical communication cycle of a Fermilab engineer

Physicists

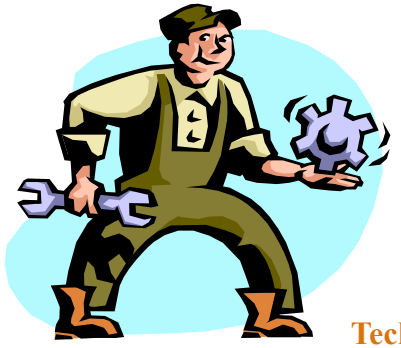


Drafters / Designers



Vendors

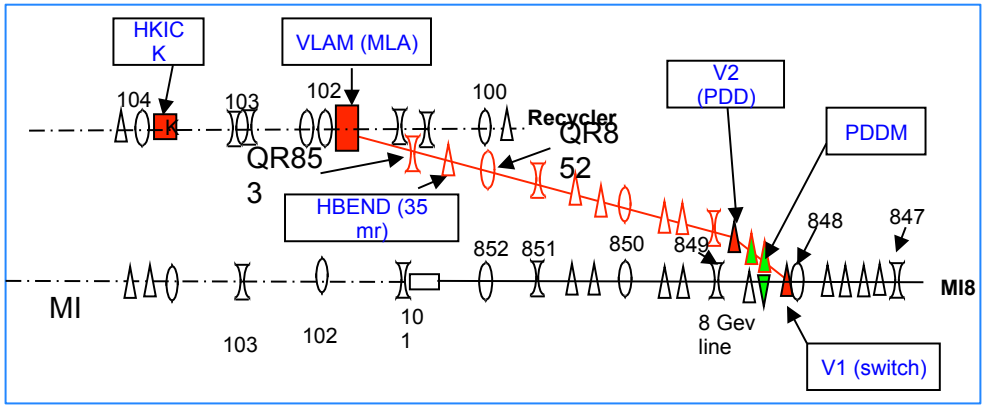
Engineers

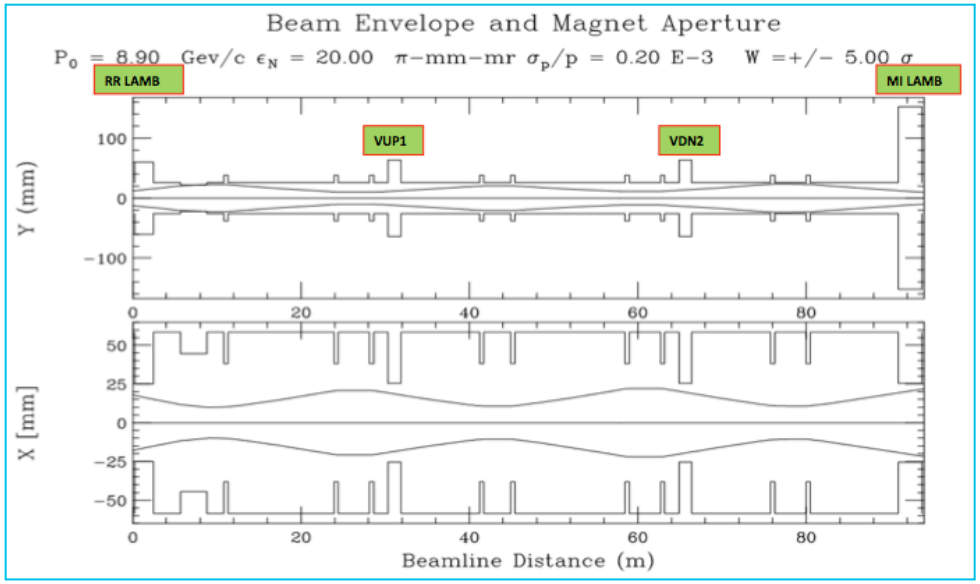


Technicians

Machinists

Example of physicists' specifications





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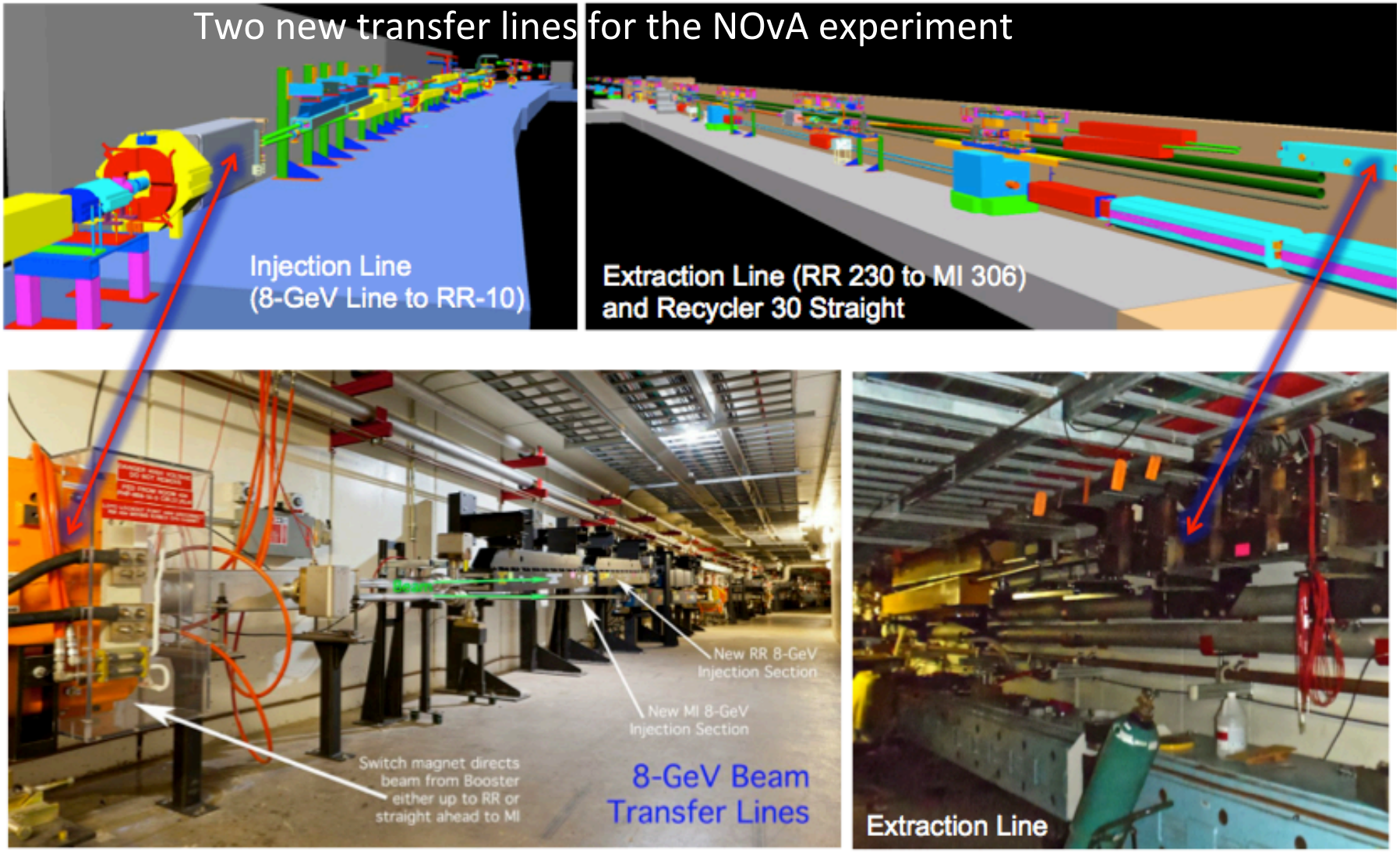
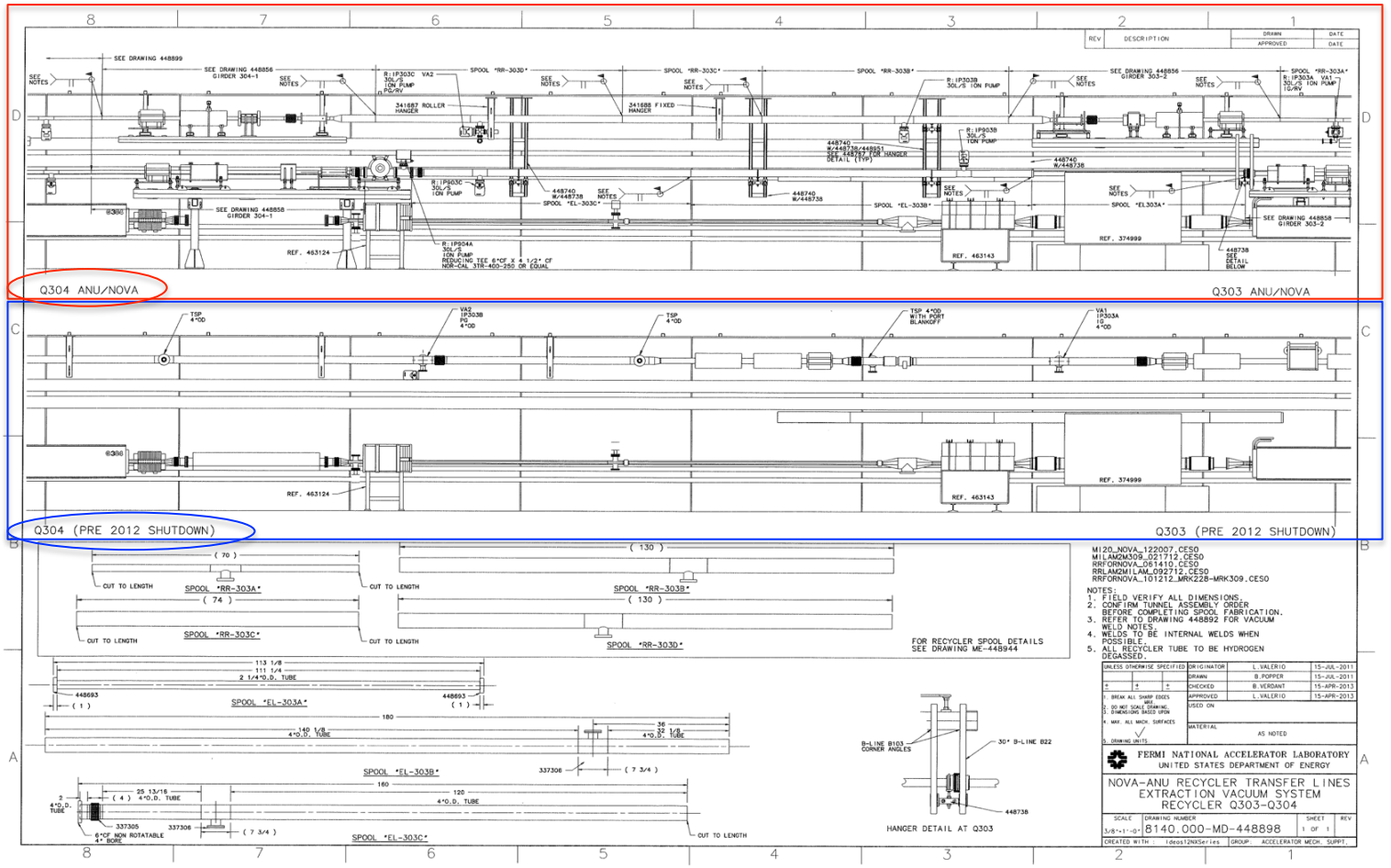
0000	M840	MARKER	0.00000	100150.54159	97752.62195	715.85533	-117.27151	0.00000	0.00000
0001	PGD_F	PGD	3.08333	100149.12879	97749.88135	715.85533	-117.82178	0.00000	0.00000
0002	PGD_D	PGD	33.12187	100134.96511	97723.39203	715.85533	-118.92235	0.00000	0.00000
0003	PGD_D	PGD	52.33016	100125.62382	97706.60837	715.85533	-120.02291	0.00000	0.00000
0004	PGD_F	PGD	82.36871	100110.45321	97680.68258	715.85533	-121.12345	0.00000	0.00000
0005	PGD_F	PGD	101.57700	100100.47420	97664.27007	715.85533	-122.22402	0.00000	0.00000
0006	PGD_D	PGD	131.61554	100084.31905	97638.94608	715.85533	-123.32458	0.00000	0.00000
0007	PGD_D	PGD	150.82384	100073.71704	97622.92895	715.85533	-124.42512	0.00000	0.00000
0008	PGD_F	PGD	180.86238	100056.60118	97598.24411	715.85533	-125.52569	0.00000	0.00000
0009	PGD_F	PGD	198.86235	100046.10336	97583.62261	715.85533	-126.62625	0.00000	0.00000
0010	PDD	8DH	212.98767	100037.66797	97572.29266	715.85533	-127.72679	0.00000	0.00000
0011	PDD	8DH	222.15499	100032.05031	97565.04829	715.85533	-128.82735	0.00000	0.00000
0012	PGD_D	PGD	231.32199	100026.29474	97557.91341	715.85533	-129.92792	0.00000	0.00000
0013	PGD_D	PGD	248.11363	100015.48997	97545.05995	715.85533	-131.02846	0.00000	0.00000
0014	PDD	8DH	262.23896	100006.20981	97534.41091	715.85533	-132.12902	0.00000	0.00000
0015	PDD	8DH	271.40627	100000.05266	97527.61911	715.85533	-133.22959	0.00000	0.00000
0016	PGD_F	PGD	280.57328	99993.76642	97520.94706	715.85533	-134.33016	0.00000	0.00000
0017	HT846	BLHC	294.08367	99984.32226	97511.28590	715.85533	-134.88045	0.00000	0.00000
0018	QT846	MRQ	295.00025	99983.67549	97510.63643	715.85533	-134.88045	0.00000	0.00000
0019	HP846	8GBPM	296.48975	99982.62446	97509.58100	715.85533	-134.88045	0.00000	0.00000
0020	PGD_F	PGD	297.36475	99982.00703	97508.96099	715.85533	-135.43072	0.00000	0.00000
0021	PDD	8DH	311.49008	99971.93685	97499.05569	715.85533	-136.53126	0.00000	0.00000
0022	PDD	8DH	320.65739	99965.27655	97492.75654	715.85533	-137.63182	0.00000	0.00000
0023	PDD	8DH	332.30344	99956.64916	97484.93375	715.85533	-138.73239	0.00000	0.00000
0024	QT847	MRQ	340.93892	99950.15494	97479.24199	715.85533	-139.28266	0.00000	0.00000
0025	Q847_2	SQA-2_REV	342.94925	99948.63124	97477.93060	715.85533	-139.28266	0.00000	0.00000
0026	Q847_2	SQA-2_REV	343.64196	99948.10621	97477.47873	715.85533	-139.28266	0.00000	0.00000
0027	VP847	8GBPM	345.16799	99946.94957	97476.48325	715.85533	-139.28266	0.00000	0.00000
0028	VT847	MCV_CERN	347.58491	99945.11770	97474.90663	715.85533	-139.28266	0.00000	0.00000
0029	PDD	8DH	349.57441	99943.60978	97473.60882	715.85533	-139.83293	0.00000	0.00000
0030	PDD	8DH	360.74141	99935.05734	97466.42862	715.85533	-140.93349	0.00000	0.00000
0031	PDD	8DH	369.90872	99927.93318	97460.65929	715.85533	-142.03406	0.00000	0.00000
0032	PDD	8DH	381.07572	99919.11127	97453.81287	715.85533	-143.13460	0.00000	0.00000
0033	HT848	BLHC	389.66433	99912.23708	97448.66414	715.85533	-143.68487	0.00000	0.00000
0034	QT848	MRQ	390.70591	99911.39780	97448.04729	715.85533	-143.68487	0.00000	0.00000
0035	HP848	8GBPM	391.94541	99910.39905	97447.31322	715.85533	-143.68487	0.00000	0.00000
0036	Q848_2	SQA-2_REV	393.29958	99909.30790	97446.51125	715.85533	-143.68487	0.00000	0.00000
0037	Q848_2	SQA-2_REV	393.99229	99908.74974	97446.10101	715.85533	-143.68487	0.00000	0.00000
0038	PDD	8DH	423.11559	99885.28299	97428.85344	715.85536	-144.23516	0.00006	0.00000
0039	PDD	8DH	432.28290	99877.83838	97423.50399	715.85536	-145.33573	0.00006	0.00000
0040	VT849	BLVC	447.33138	99865.42325	97415.00012	715.85538	-145.88600	0.00006	0.00000
0041	Q849_2	SQA-2	448.49284	99864.46165	97414.34872	715.85538	-145.88600	0.00006	0.00000
0042	Q849_2	SQA-2	449.18555	99863.88814	97413.96022	715.85538	-145.88600	0.00006	0.00000
0043	VP849	8GBPM	450.71159	99862.62469	97413.10436	715.85538	-145.88600	0.00006	0.00000
0044	PDD	8DH	455.96199	99858.27776	97410.15972	715.85539	-146.43627	0.00006	0.00000
0045	PDD	8DH	465.12930	99850.63319	97405.10014	715.85540	-147.53683	0.00006	0.00000
0046	HT850	MCH_CERN	487.00393	99832.10620	97393.47087	715.85542	-148.08713	0.00006	0.00000
0047	Q850_2	SQA-2_REV	489.51426	99829.97530	97392.14384	715.85542	-148.08713	0.00006	0.00000
0048	Q850_2	SQA-2_REV	490.20697	99829.38730	97391.77765	715.85542	-148.08713	0.00006	0.00000
0049	HP850	8GBPM	491.73301	99828.09191	97390.97095	715.85543	-148.08713	0.00006	0.00000
0050	PDD	8DH	498.69767	99822.17994	97387.28922	715.85543	-148.63740	0.00006	0.00000
0051	PDD	8DH	507.86498	99814.34668	97382.52698	715.85544	-149.73794	0.00006	0.00000
0052	MW851	MWIRE	529.36140	99795.71521	97371.80532	715.85546	-150.28820	0.00006	0.00000
0053	VT851	MCV_CERN	531.45523	99793.89666	97370.76754	715.85546	-150.28820	0.00006	0.00000
0054	Q851_2	SQA-2_REV	533.96556	99791.71636	97369.52333	715.85546	-150.28820	0.00006	0.00000
0055	Q851_2	SQA-2_REV	534.65826	99791.11473	97369.18000	715.85547	-150.28820	0.00006	0.00000
0056	VP851	8GBPM	536.18430	99789.78931	97368.42364	715.85547	-150.28820	0.00006	0.00000
0057	HP852	8GBPM	587.48583	99745.23241	97342.99669	715.85552	-150.28820	0.00006	0.00000
0058	Q852_2	SQA-2	588.31916	99744.50864	97342.58367	715.85552	-150.28820	0.00006	0.00000
0059	Q852_2	SQA-2	589.01187	99743.90700	97342.24033	715.85552	-150.28820	0.00006	0.00000
0060	HT852	MCH_CERN	590.71924	99742.42410	97341.39410	715.85552	-150.28820	0.00006	0.00000
0061	MW852	MWIRE	592.49624	99740.88072	97340.51335	715.85552	-150.28820	0.00006	0.00000
0062	AOLAM	AOLAM	626.14073	99711.65948	97323.83789	715.85556	-151.29088	0.00006	0.00000
0063	M101	MARKER	636.77785	99702.30404	97318.77660	715.85557	-152.29356	0.00006	0.00000
0064	HQ_D	X3Q84-2	636.77785	99702.30404	97318.77660	715.85557	-152.29356	0.00006	0.00000
0065	MI101	MARKER	640.27784	99699.20535	97317.14931	715.85557	-152.29356	0.00006	0.00000
0066	HQ101	X3Q84-2	640.27784	99699.20535	97317.14931	715.85557	-152.29356	0.00006	0.00000
0067	M102	MARKER	693.49899	99652.08645	97292.40460	715.85563	-152.29356	0.00006	0.00000
0068	HQ_F	X3Q84-2	693.49899	99652.08645	97292.40460	715.85563	-152.29356	0.00006	0.00000

What specifications develop into…



Communicating ideas to build something real



Sample of installation drawings for NOvA

- 29 before & after vacuum system drawings like this were created for three regions of the accelerator
- Magnet installation drawings were separate
- Hundreds of supporting (part) drawings

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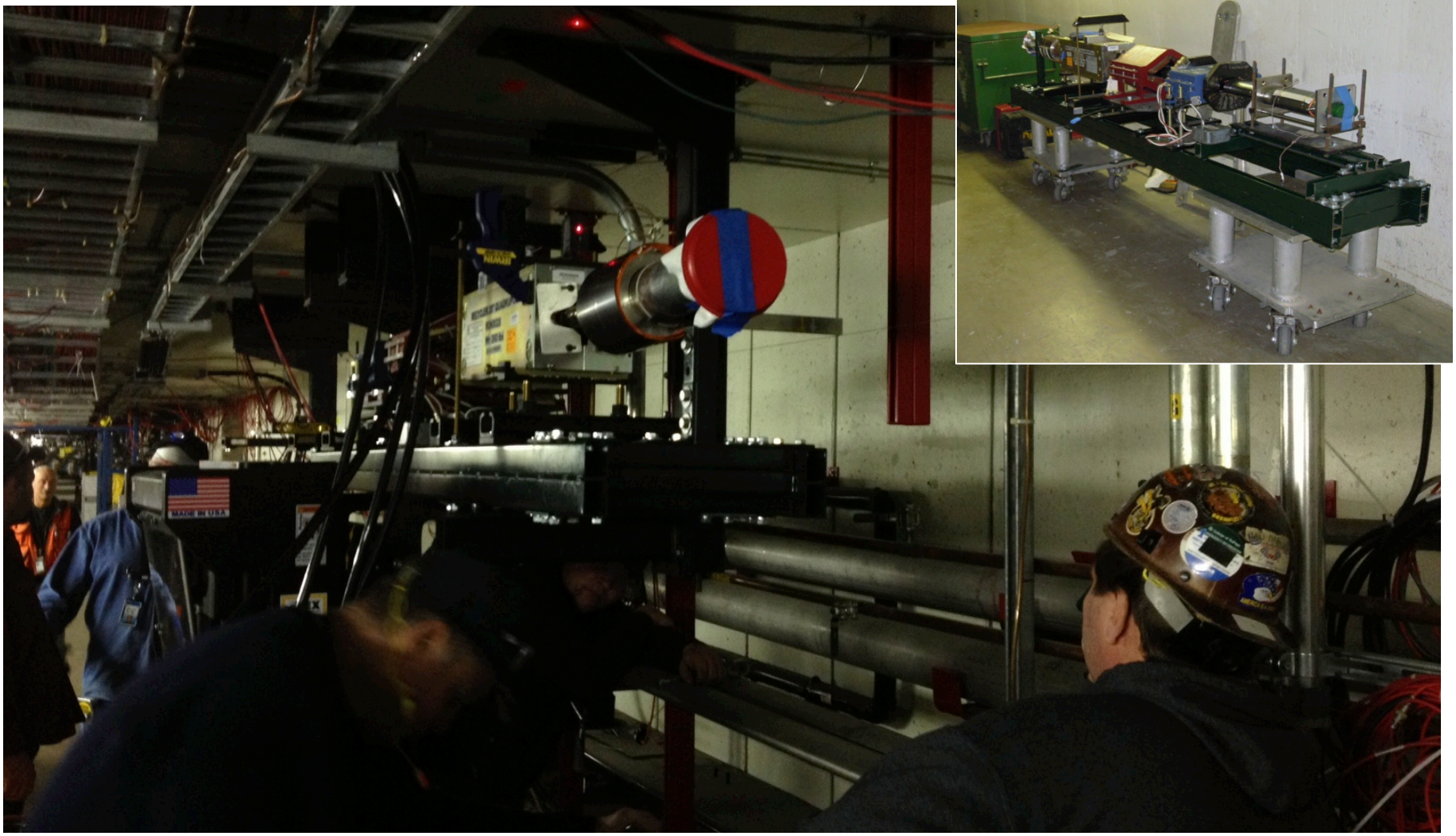
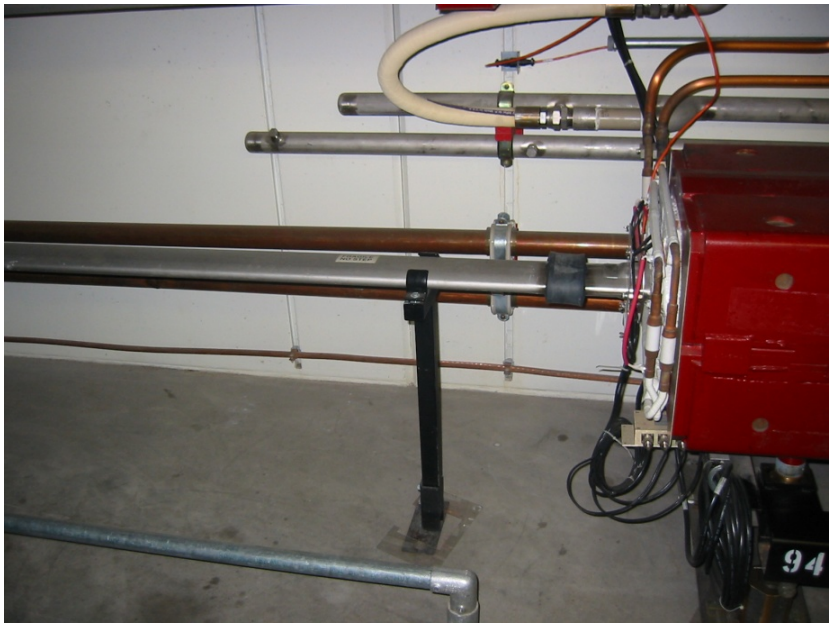
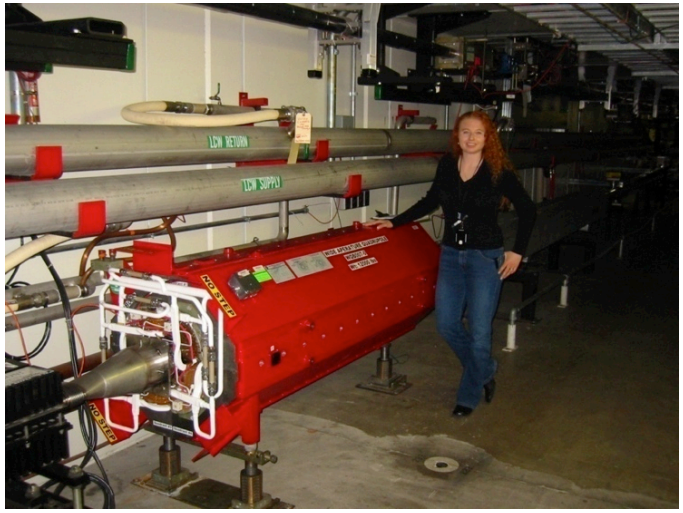
Efficient installation in radiation areas - NOvA



Example upgrade – wide aperture quadrupole magnet





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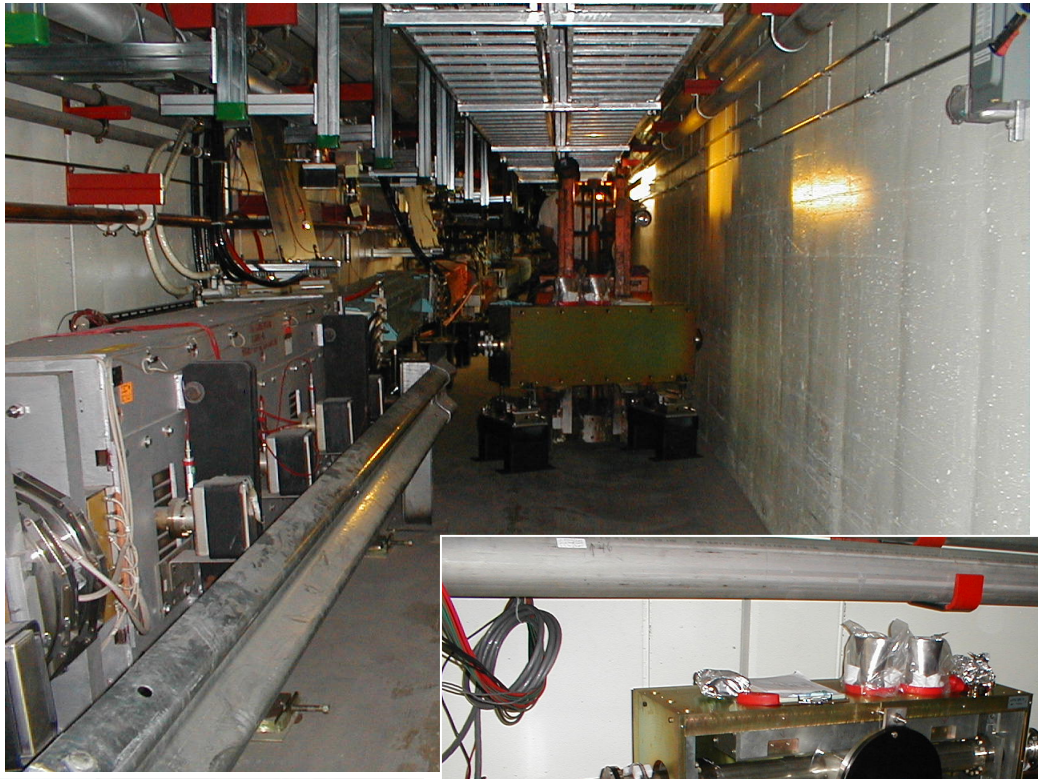
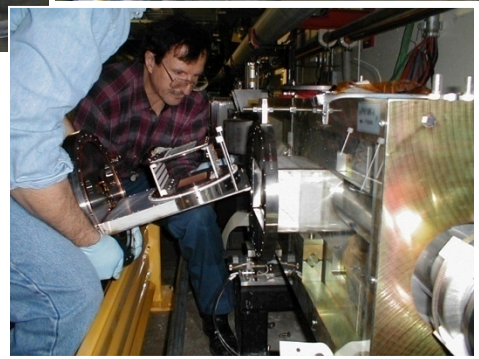
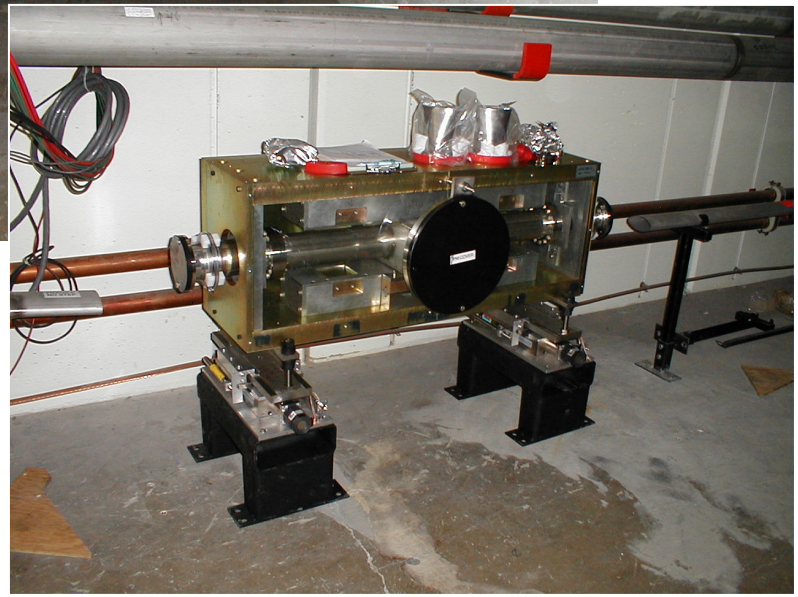
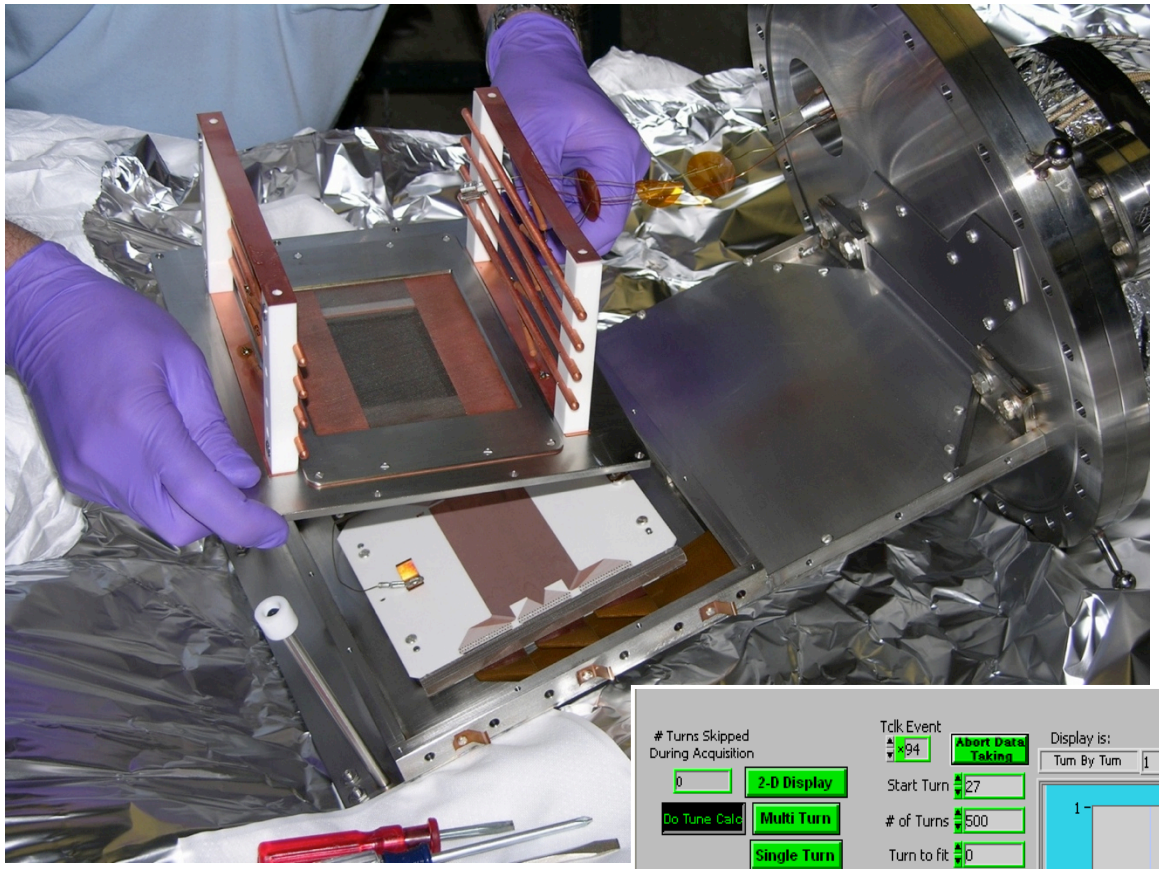
Example installation – ion profile monitor (IPM)

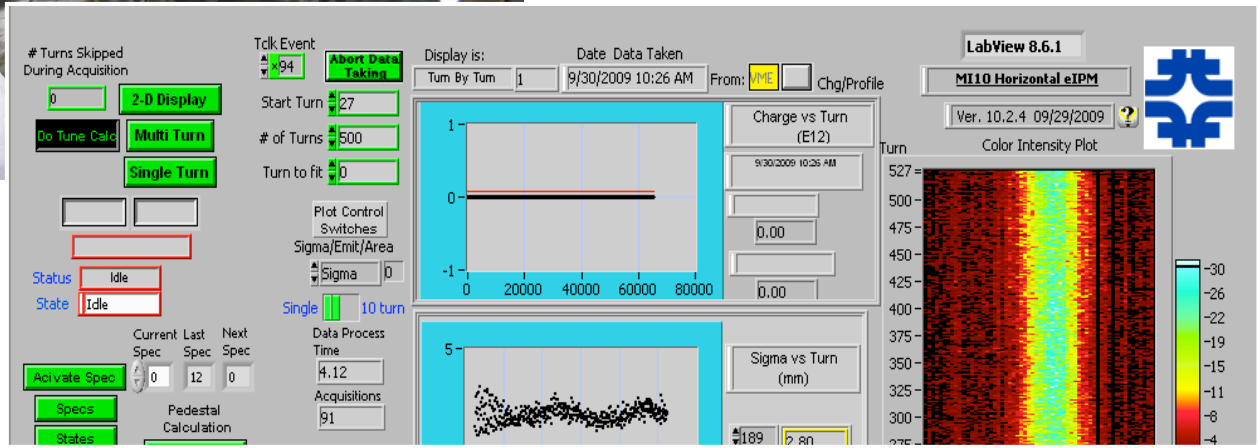






Inside an ion profile monitor (IPM)





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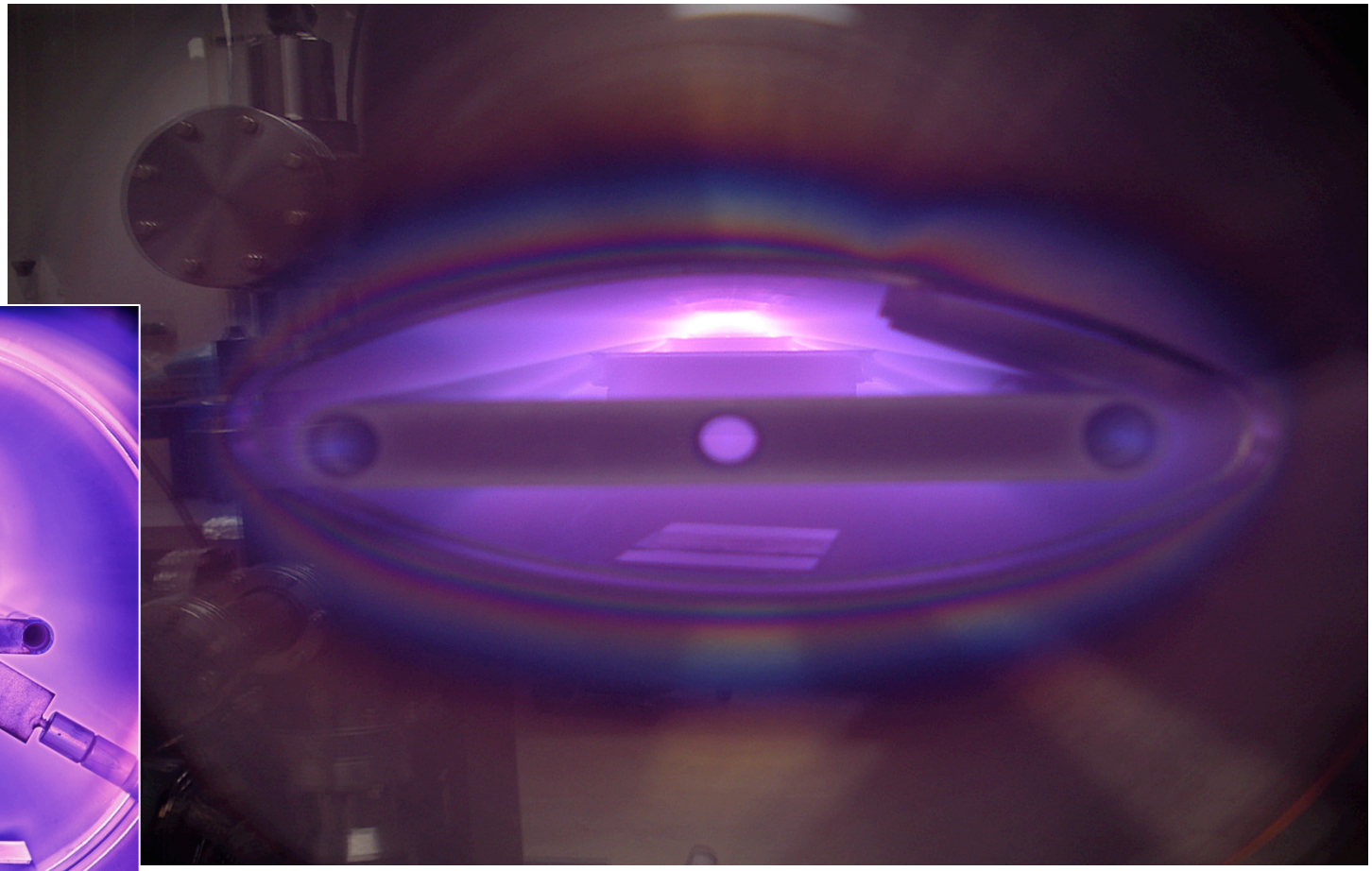
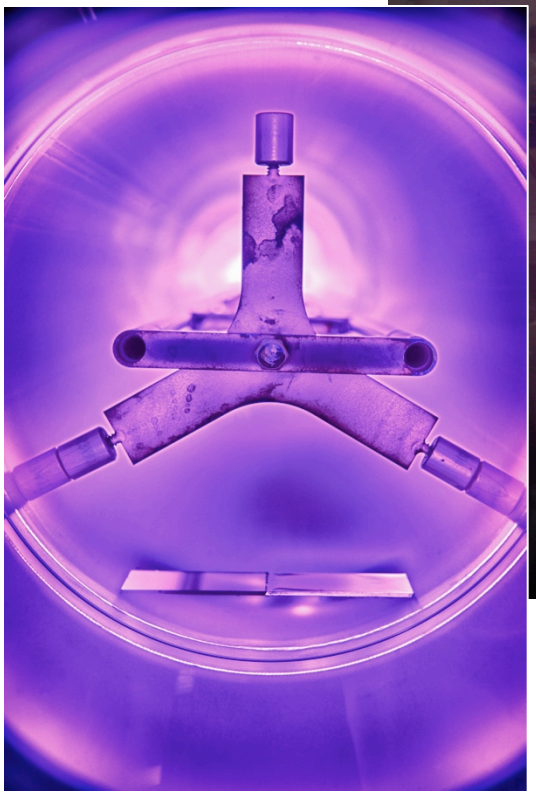
More small details – R&D titanium nitride coating





Introduction to vacuum system design

Factors that affect vacuum system design to reach specified pressure:

- Volume of system
- Materials (outgassing rates)
- Pump size and spacing
- Conductance to all volumes (to pumps, and avoiding virtual leaks)
- Cleanliness of everything within the system

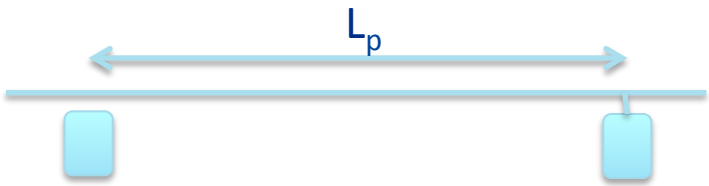
Some starting equations:

$PV=nRT$

$Q=SP$

$Q=C\Delta P$

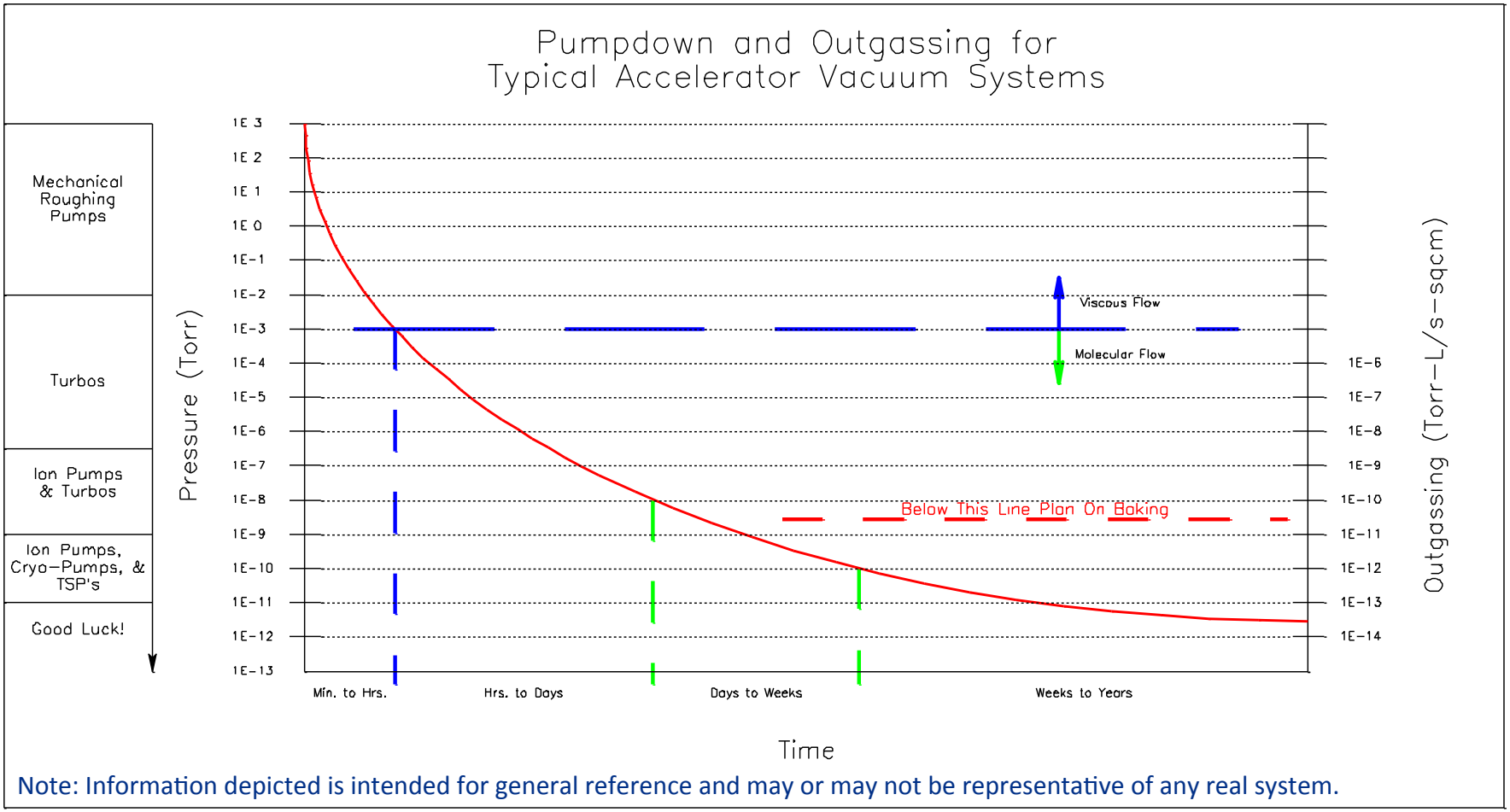
$P_p=q_D*B*L_p/S$



P=pressure
V=volume
n=number of moles
R=universal gas constant
T=temperature
Q=gas flow

S=pump speed
C=conductance
P_p=pressure at the pump
q_D=specific outgassing rate
B=inside tube perimeter
L_p=pump spacing

Vacuum system basics



Note: Information depicted is intended for general reference and may or may not be representative of any real system.

Graph from "Accelerator Vacuum 101" by T. Anderson, 2006.

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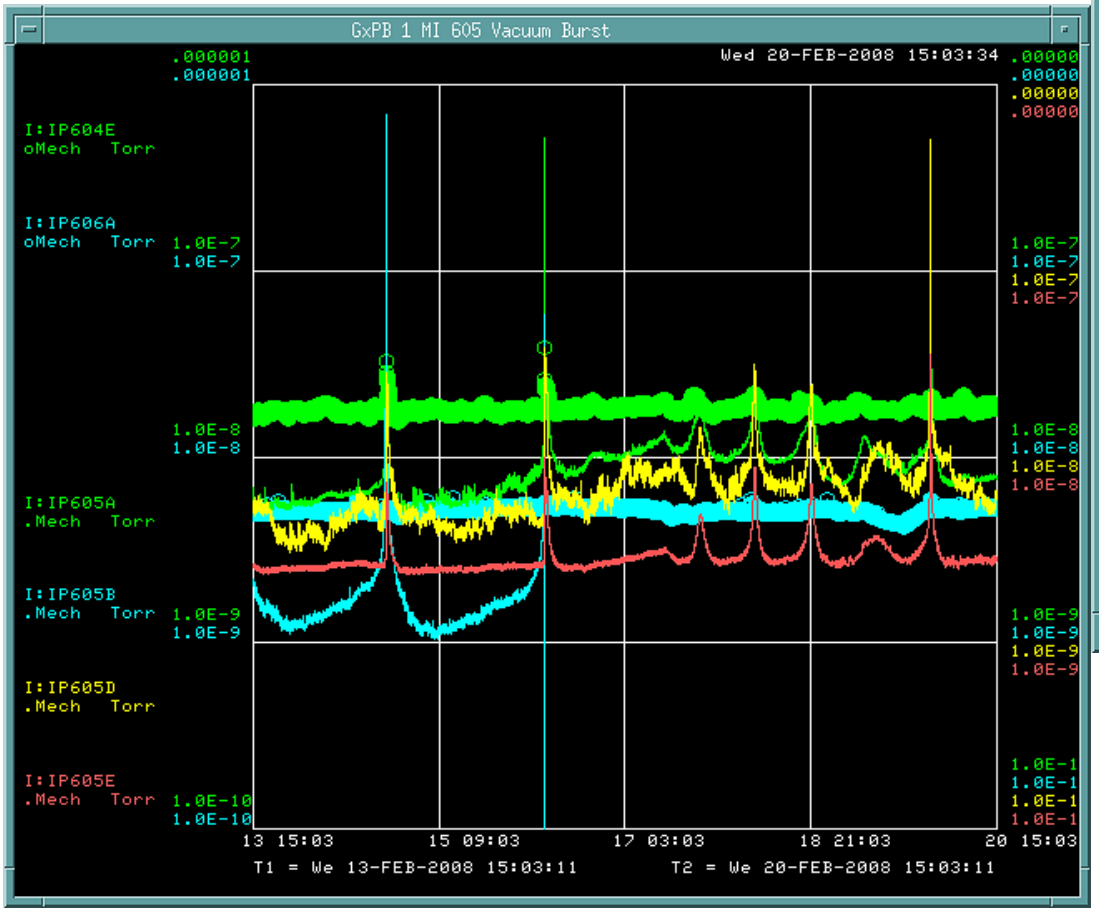
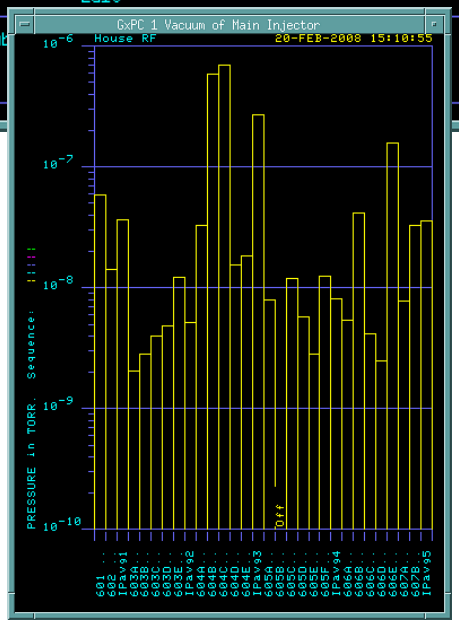
Vacuum system analysis





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Beamline design

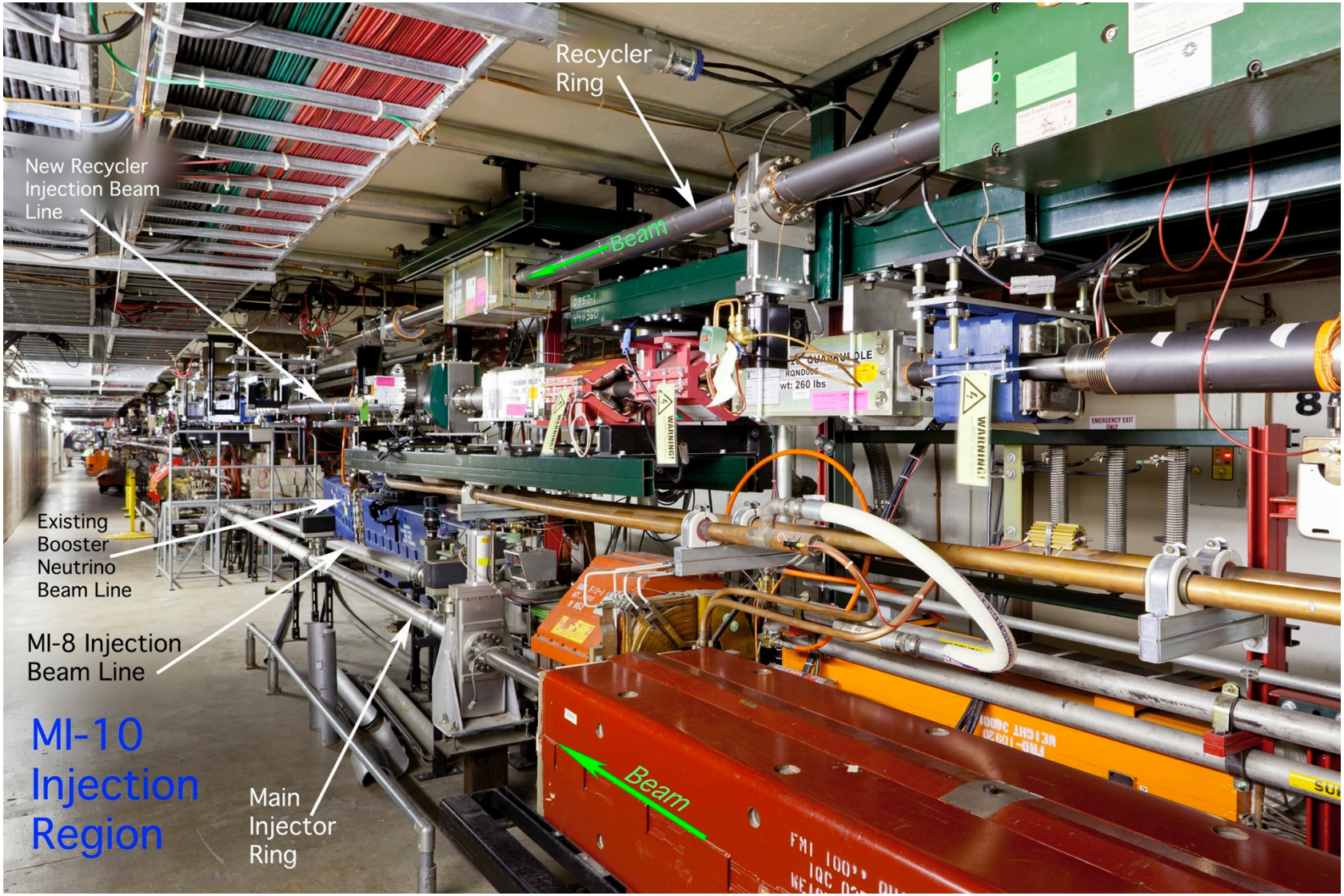

photo by M. Murphy

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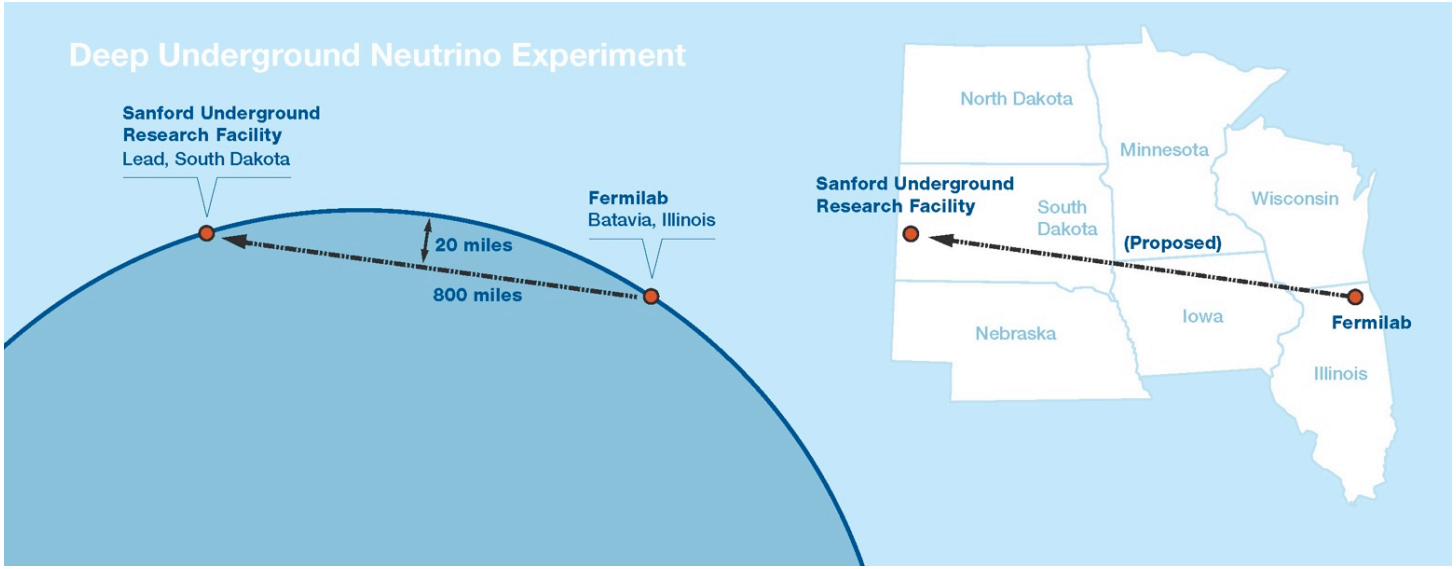
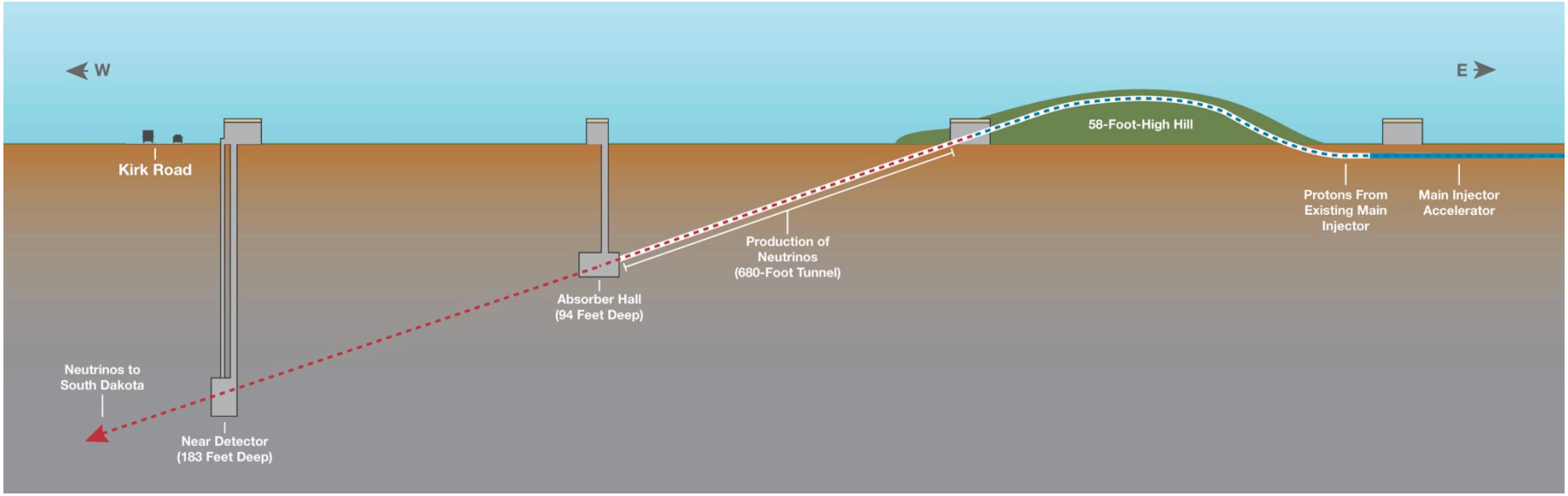
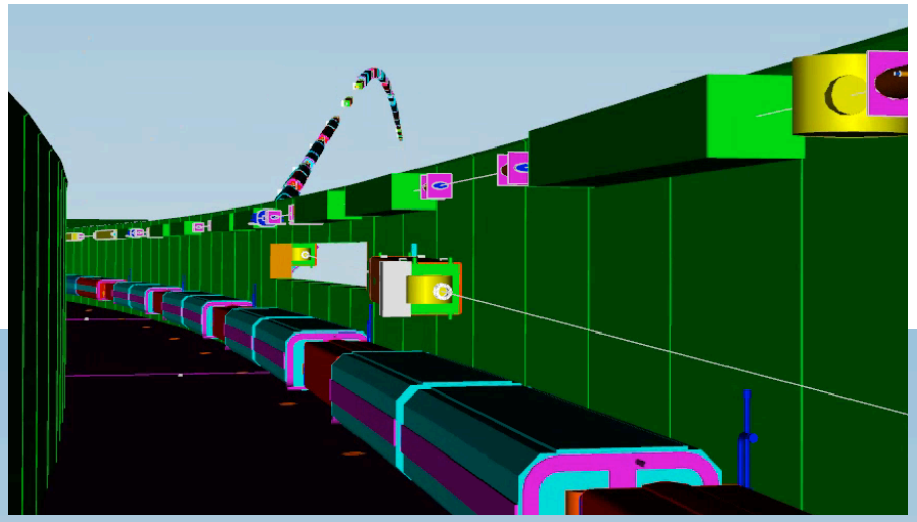
What's next? Designing a beamline for LBNF and DUNE

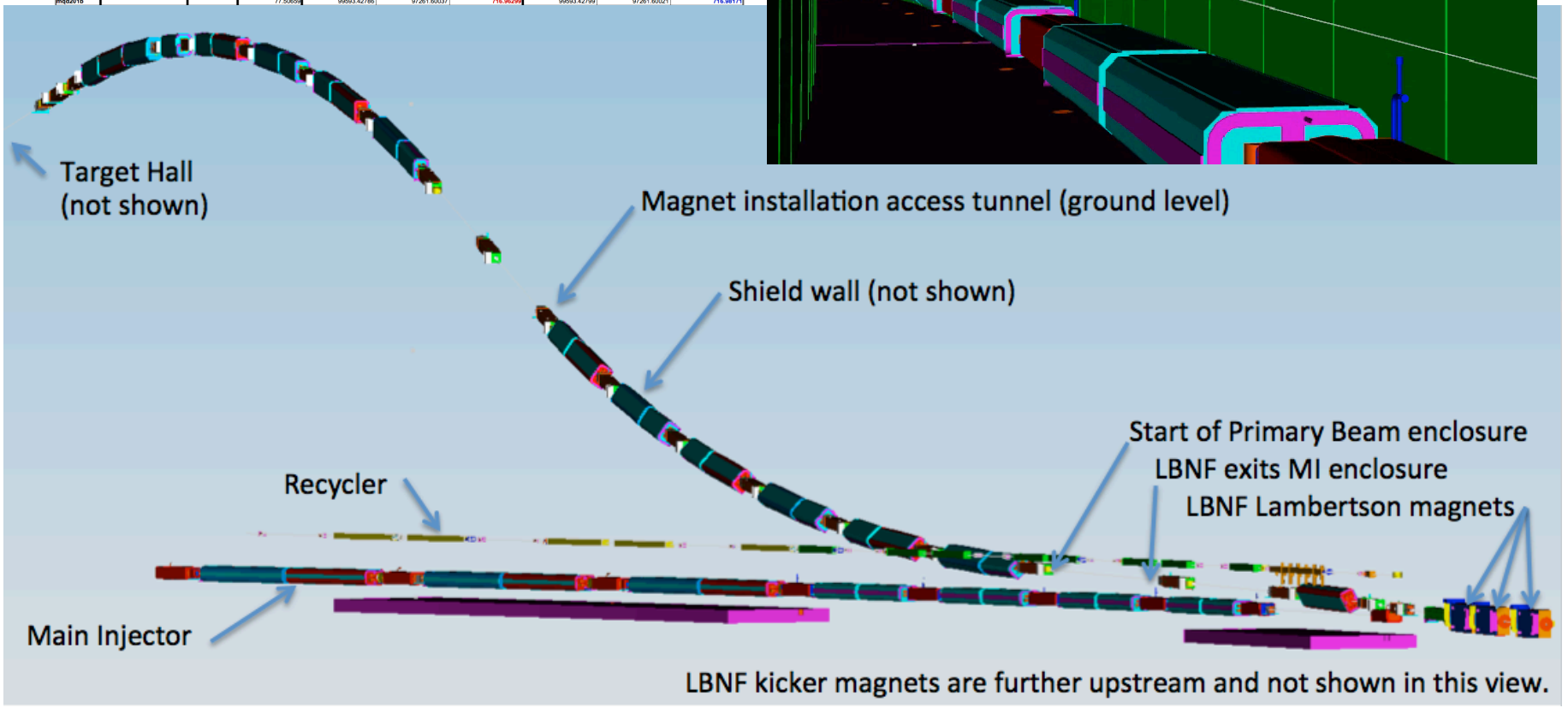




Early 3-D model of LBNF and Main Injector

Location	COMMON NAME	Type_code	Lucky13_DUSAF_02252013.txt JohnJ_BEAMSHEET coordinates				Earth Curvature Corrected coordinates			
			Distance	LTCSZ_x	LTCSZ_y	LTCSZ_z	LTCSH_X	LTCSH_Y	LTCSH_H	
			(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	
LUCKY13			0.00000	99662.03555	97297.63003	715.72410	99662.03561	97297.62996	715.74162	
mvv			0.75577	99661.36643	97297.27864	715.72410	99661.36649	97297.27857	715.74163	
LAM10	MI LAMBERTSON	MILAM	0.75577	99661.36643	97297.27864	715.72410	99661.36649	97297.27857	715.74163	
mvv			9.94211	99653.23341	97293.00754	715.74120	99653.23348	97293.00747	715.75886	
mqq			11.23955	99652.08474	97292.40431	715.74684	99652.08481	97292.40423	715.76371	
Q102	3Q84 (MI Q102)	3Q84	18.23954	99645.88741	97289.14976	715.77487	99645.88748	97289.14968	715.79265	
mqq			18.23954	99645.88741	97289.14976	715.77487	99645.88748	97289.14968	715.79265	
mvv			19.40614	99644.85458	97288.60736	715.78013	99644.85465	97288.60728	715.79792	
LAM11A	MI LAMBERTSON	MILAM	19.40614	99644.85458	97288.60736	715.78013	99644.85465	97288.60728	715.79792	
mvv			28.59249	99636.72180	97284.33639	715.85373	99636.72187	97284.33631	715.87165	
mvv			30.60404	99634.94101	97283.40120	715.87688	99634.94108	97283.40112	715.89483	
LAM11B	MI LAMBERTSON	MILAM	30.60404	99634.94101	97283.40120	715.87688	99634.94108	97283.40112	715.89483	
mvv			39.79030	99626.80889	97279.13058	715.91473	99626.80897	97279.13049	715.93283	
mgm			42.18842	99624.68618	97278.01583	715.93910	99624.68626	97278.01573	715.97723	
V100	MI C-MAGNET	CMG_1_REV	42.18842	99624.68618	97278.01583	715.93910	99624.68626	97278.01573	715.97723	
mgm			53.18843	99614.94995	97272.90280	716.30852	99614.95004	97272.90269	716.32714	
mbpm			59.61498	99609.26233	97269.91592	716.48176	99609.26243	97269.91579	716.50011	
pm201A	bpm	LBNE_BPM	59.61498	99609.26233	97269.91592	716.48176	99609.26243	97269.91579	716.50011	
mbpm			60.14829	99608.79032	97269.66804	716.49604	99608.79042	97269.66791	716.51446	
mcc			60.74621	99608.26115	97269.39015	716.51213	99608.26125	97269.39002	716.53057	
HT201	trim (h)	IDS	60.74621	99608.26115	97269.39015	716.51213	99608.26125	97269.39002	716.53057	
mcc			61.74621	99607.37614	97268.92538	716.53903	99607.37624	97268.92525	716.55748	
mqq			62.50662	99606.70315	97268.57196	716.55948	99606.70325	97268.57183	716.57794	
HQD201A	3Q60	QQU-2	62.50662	99606.70315	97268.57196	716.55948	99606.70325	97268.57183	716.57794	
mqq201a			65.00662	99604.49060	97267.41003	716.62673	99604.49071	97267.40989	716.64524	
HQD201A		QQU-2	65.00662	99604.49060	97267.41003	716.62673	99604.49071	97267.40989	716.64524	
mqq			67.50661	99602.27806	97266.24810	716.69399	99602.27817	97266.24796	716.71253	
mq103			71.25660	99598.95923	97264.50520	716.79486	99598.95935	97264.50505	716.81347	
mbpm			73.00660	99596.61393	97263.27355	716.86615	99596.61405	97263.27340	716.88481	
pm201B	bpm	LBNE_BPM	73.00660	99596.61393	97263.27355	716.86615	99596.61405	97263.27340	716.88481	
mbpm			74.43993	99596.14192	97263.02567	716.88050	99596.14204	97263.02552	716.89917	
mqq			75.00660	99595.64041	97262.76230	716.89574	99595.64053	97262.76214	716.91442	
HQD201B	3Q60	QQU-2	75.00660	99595.64041	97262.76230	716.89574	99595.64053	97262.76214	716.91442	
mqd201b			77.50659	99593.42786	97261.60037	716.96299	99593.42799	97261.60021	716.98171	





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The end. Same photo, different perspective?

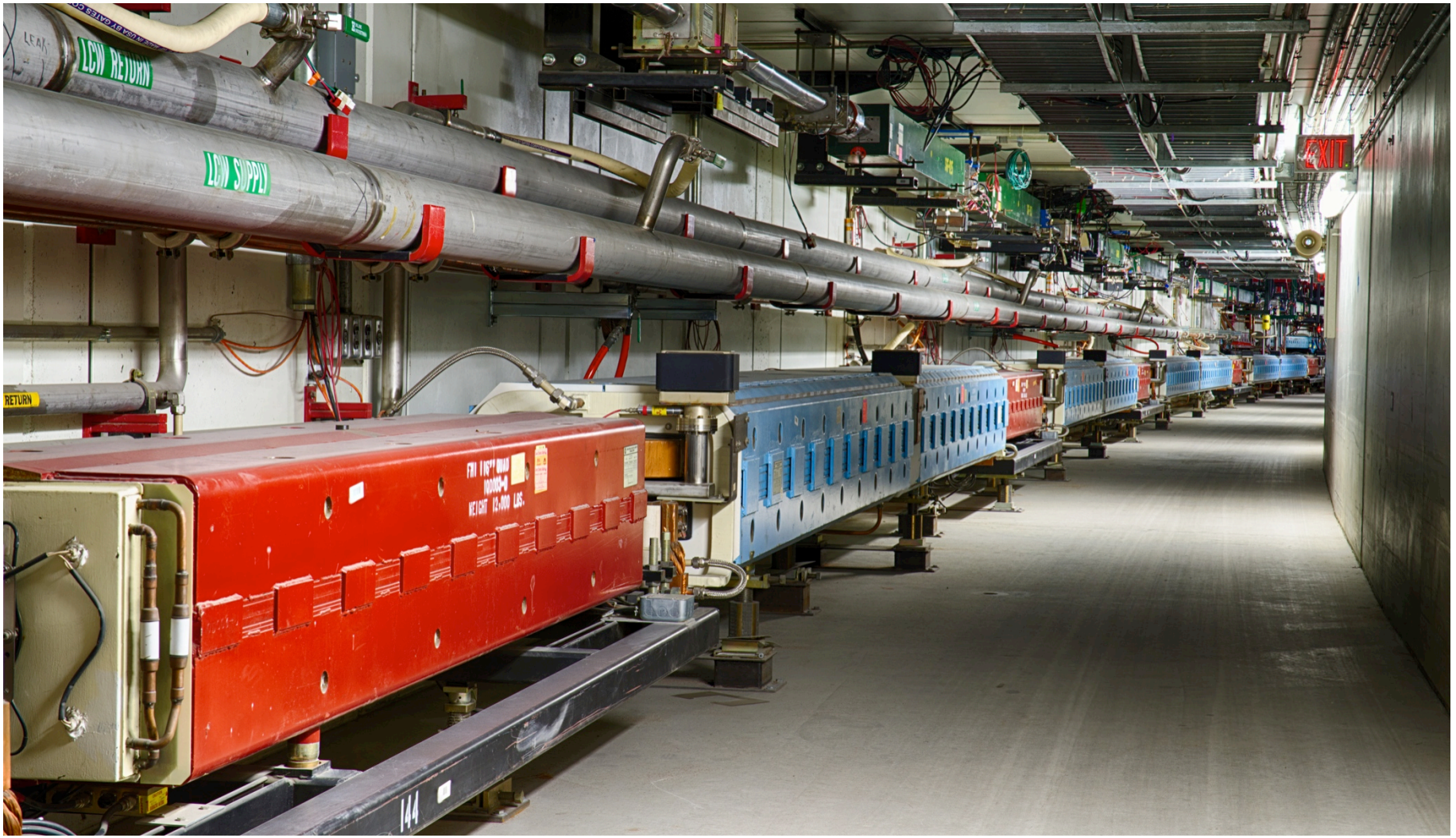

photo by R. Hahn