A Proposal For An Upgraded Booster For Project X

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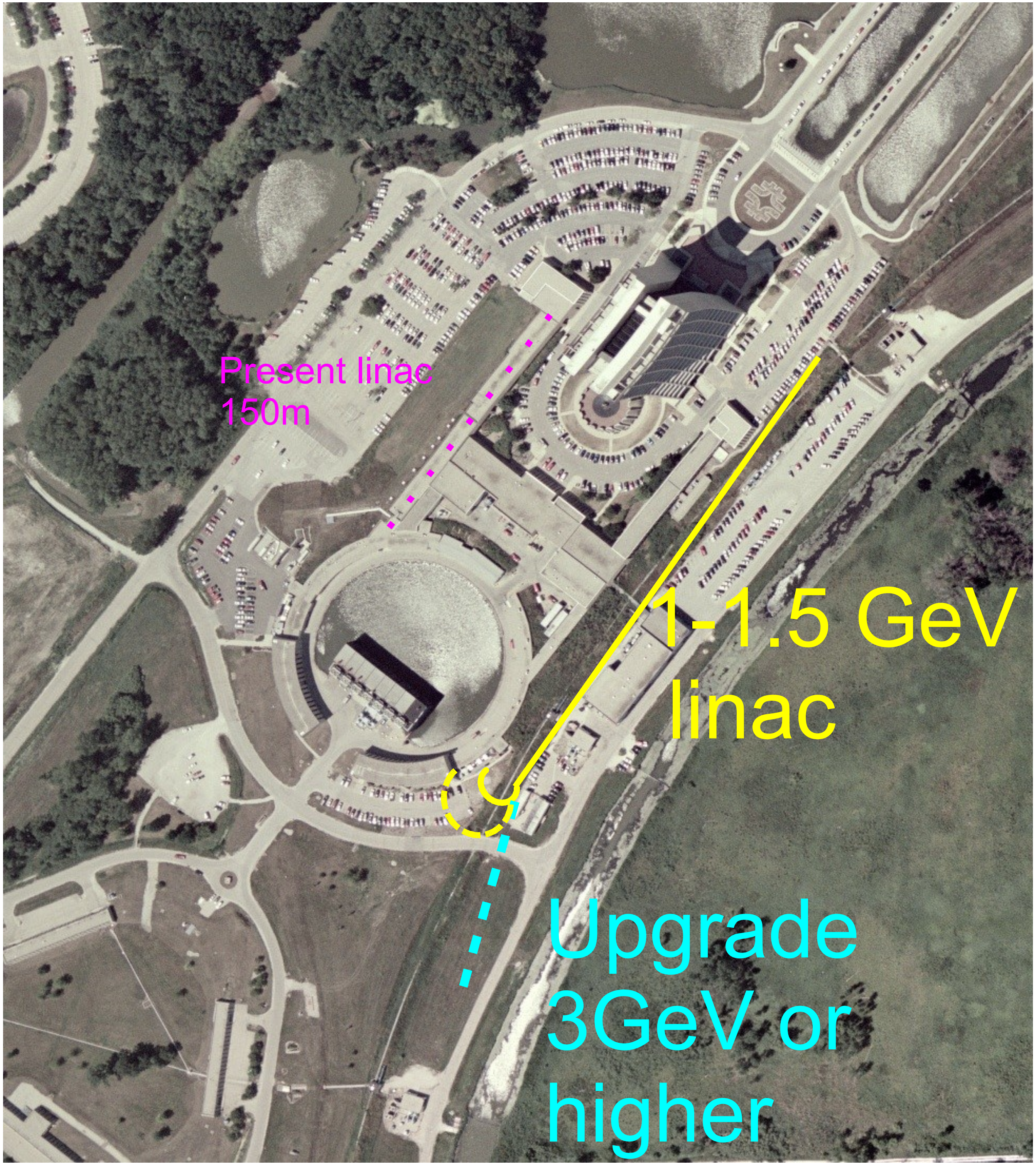
Motivation

- Lower the cost of Project X by using existing infrastructure and tunnels
  - Reduce digging
  - Use existing utilities, e.g. water, power.
  - Reuse present MI-8 line.
- The Booster RF upgrades etc. can be made Project X compatible.
  - NOVA, mu2e, etc. will require RF upgrades and possibly new cavities.
    - $30 million in savings if new cavities are built.

Proposal

- Build a new 1-1.5GeV superconducting linac for injecting into Booster
  - Linac can fit in existing switchyard.
  - There is space for linac upgrade to 3GeV or higher.
- Create a new Booster lattice that has zero dispersion sections for RF and transfer lines.
  - Proof of principle that this lattice exists (requirement given to us by PrX management)

Aerial Shot



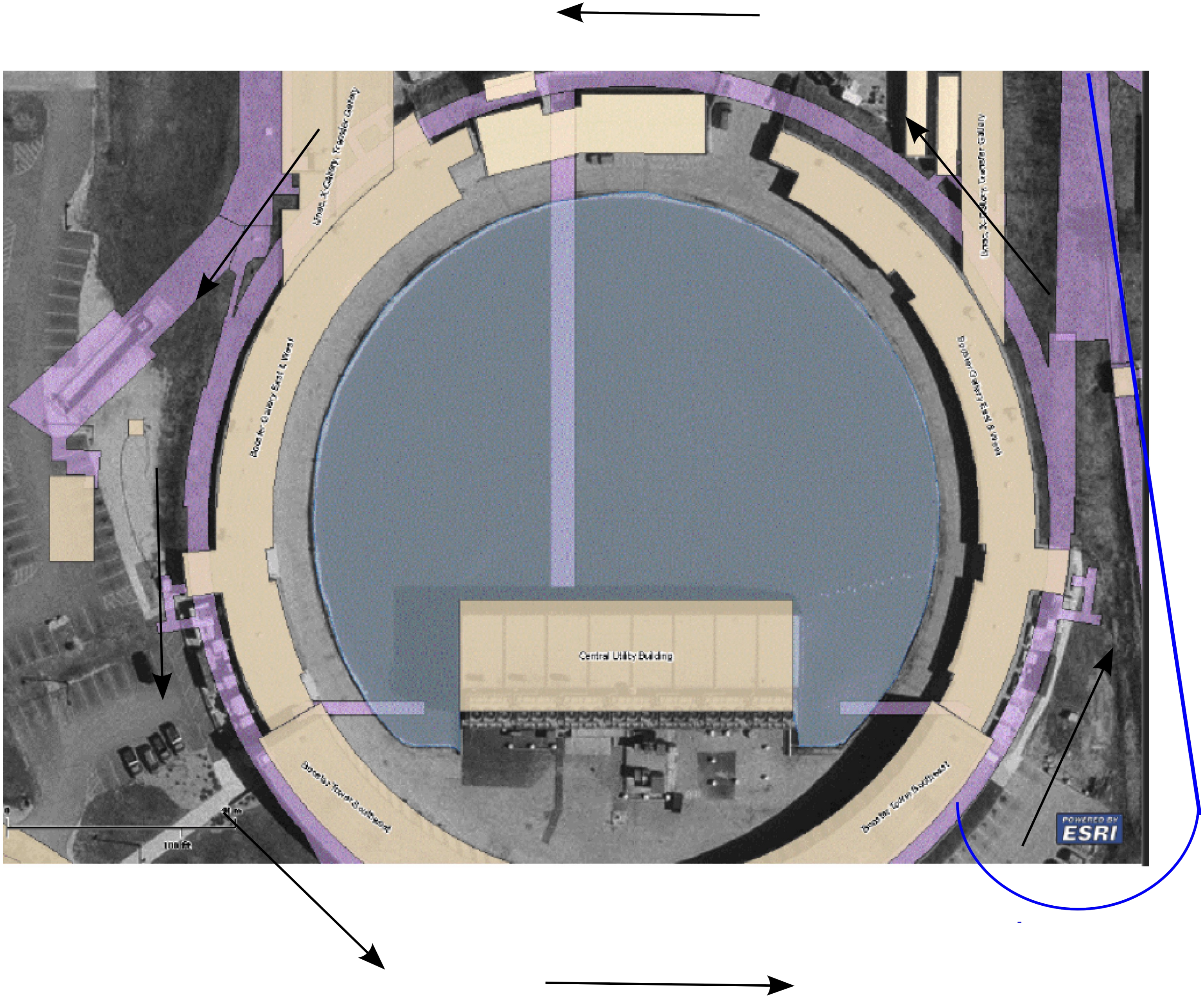
Approximate position of linac and bend. ~300m for 1-1.5 GeV linac.

For 0.1% beam loss from stripping,

1GeV protons 15.5m radius bend

1.5 GeV protons 27m radius bend

Siting 1 to 1.5 GeV linac in Switchyard Transfer Line



For 0.1% beam loss from stripping,

1GeV protons
15.5m radius bend

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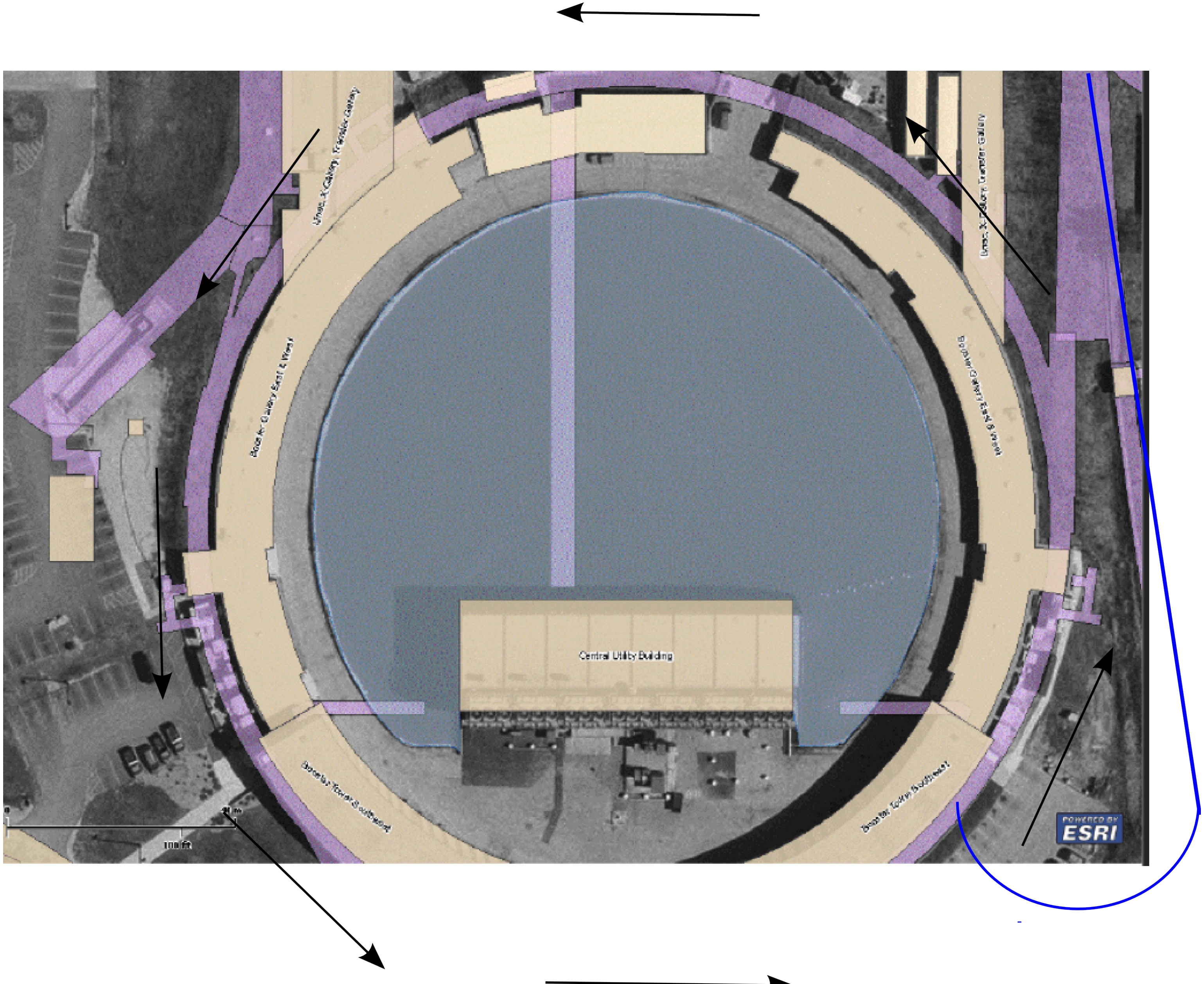
27m radius bend

Siting 1 to 1.5 GeV linac in Switchyard Transfer Line

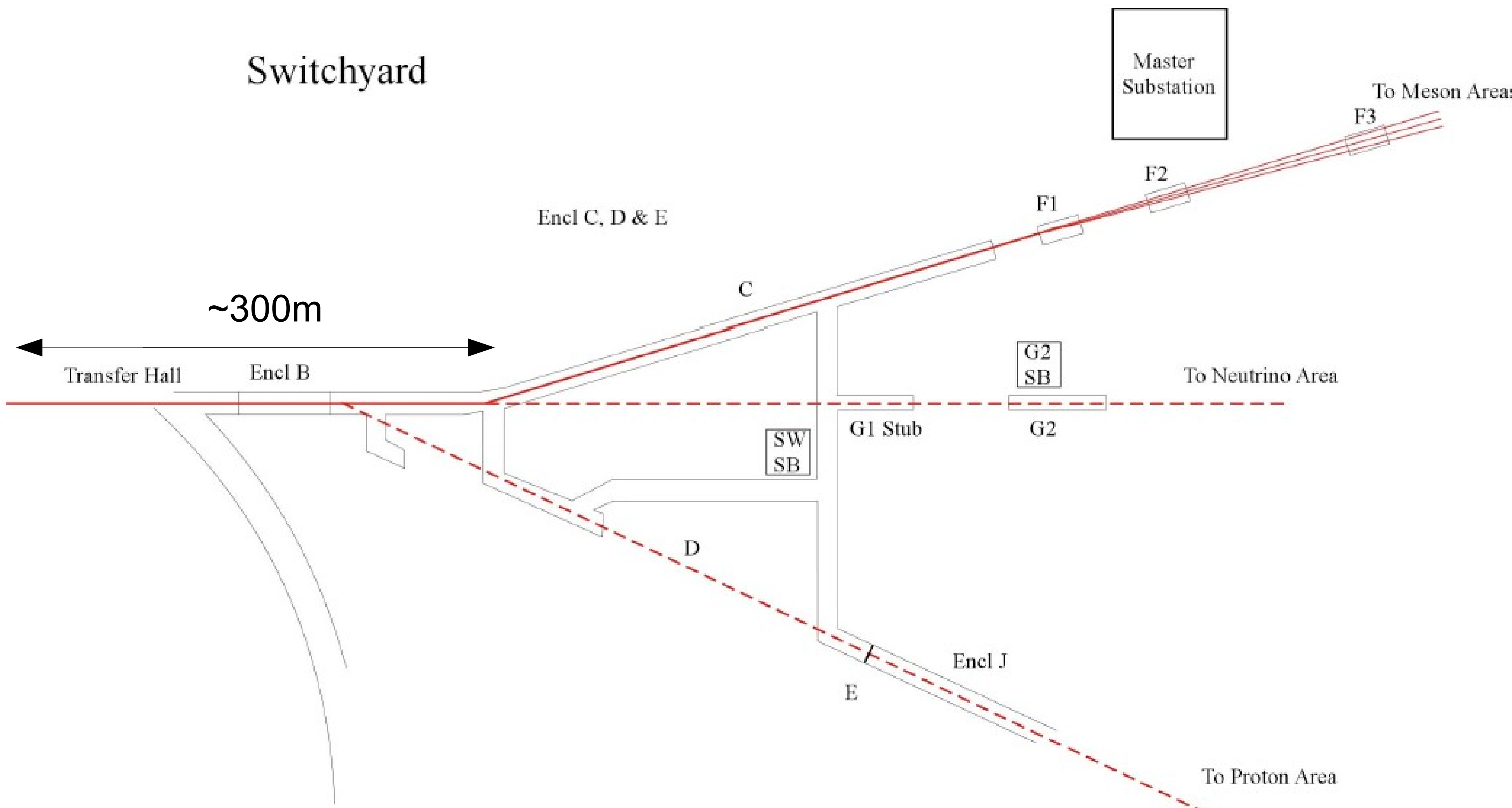


For 0.1% beam loss from stripping,

1GeV protons
15.5m radius bend

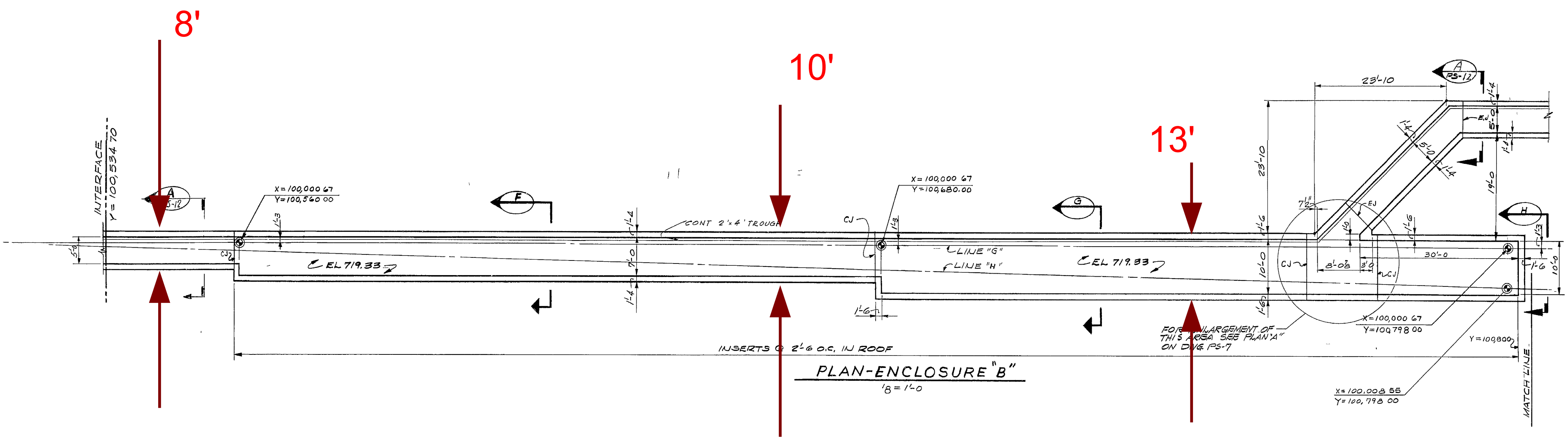
1.5 GeV protons
27m radius bend

Switchyard



Switchyard Enclosure Map

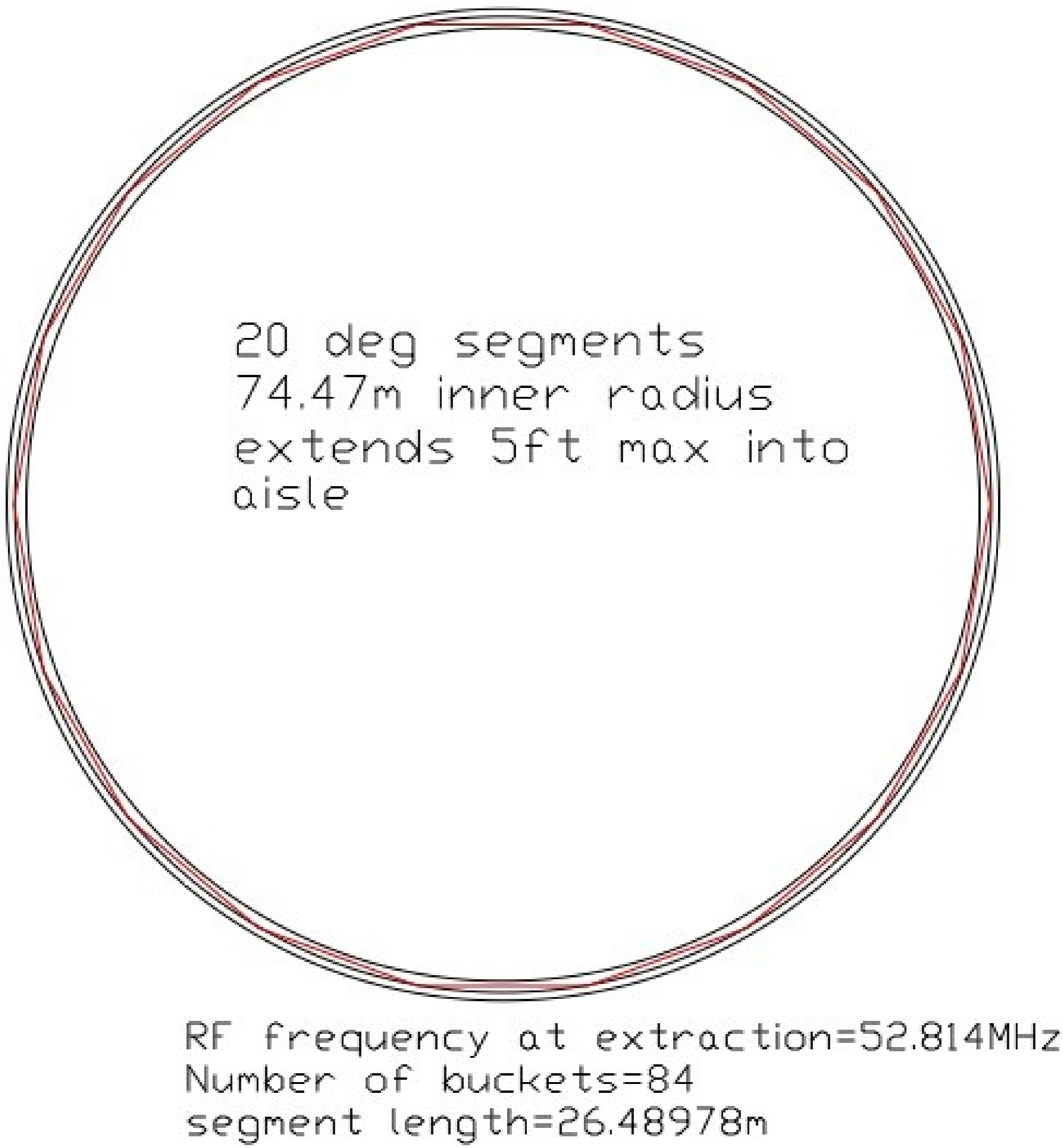
Enclosure B Plan View



New Booster Lattice

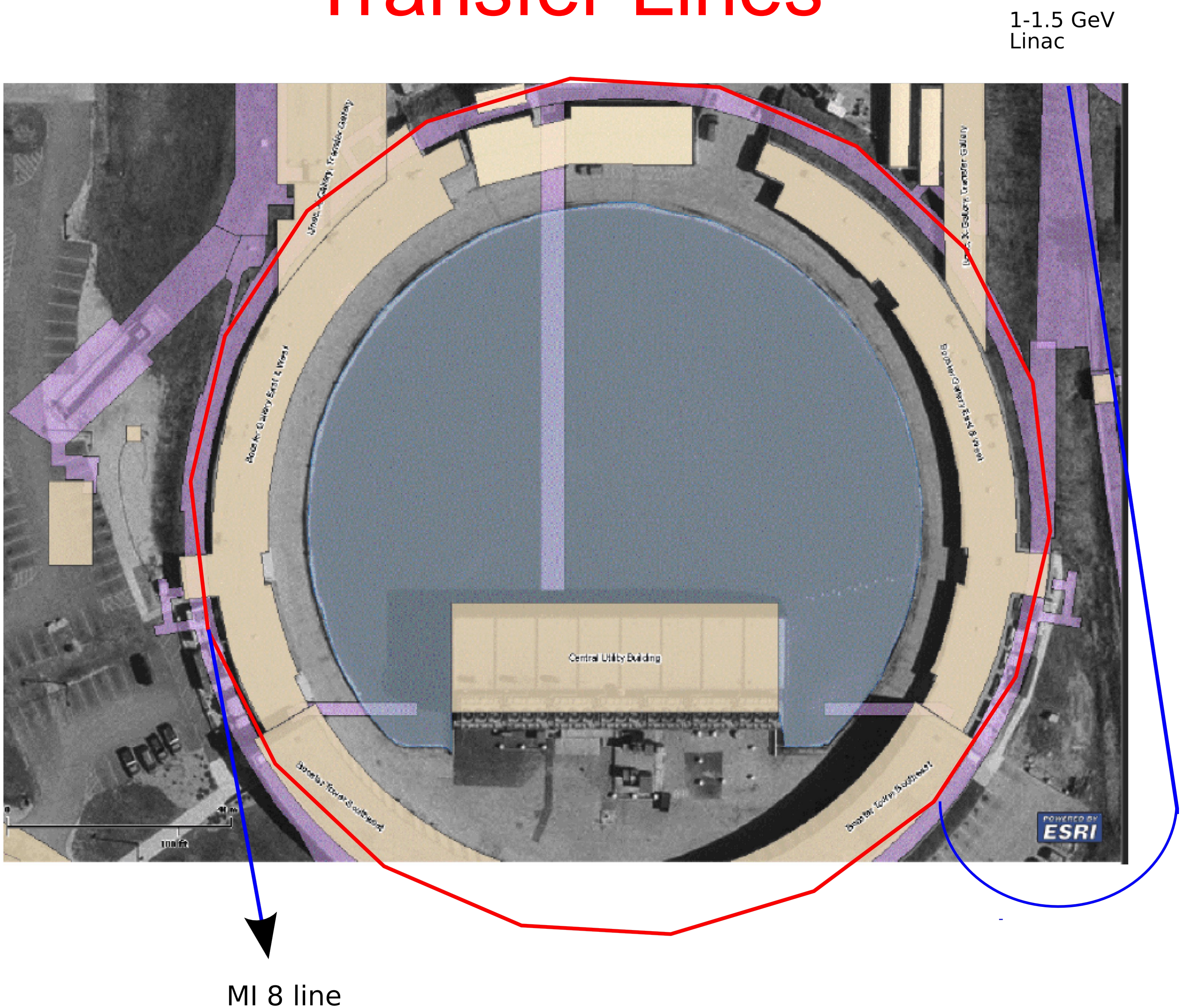
- Create a simple lattice that has zero dispersion in straight sections for RF cavities and transfer lines.
  - No stability calculations, tune shift etc.
- Must fit in the existing Booster tunnel.

18 sided (octadecagon) Ring

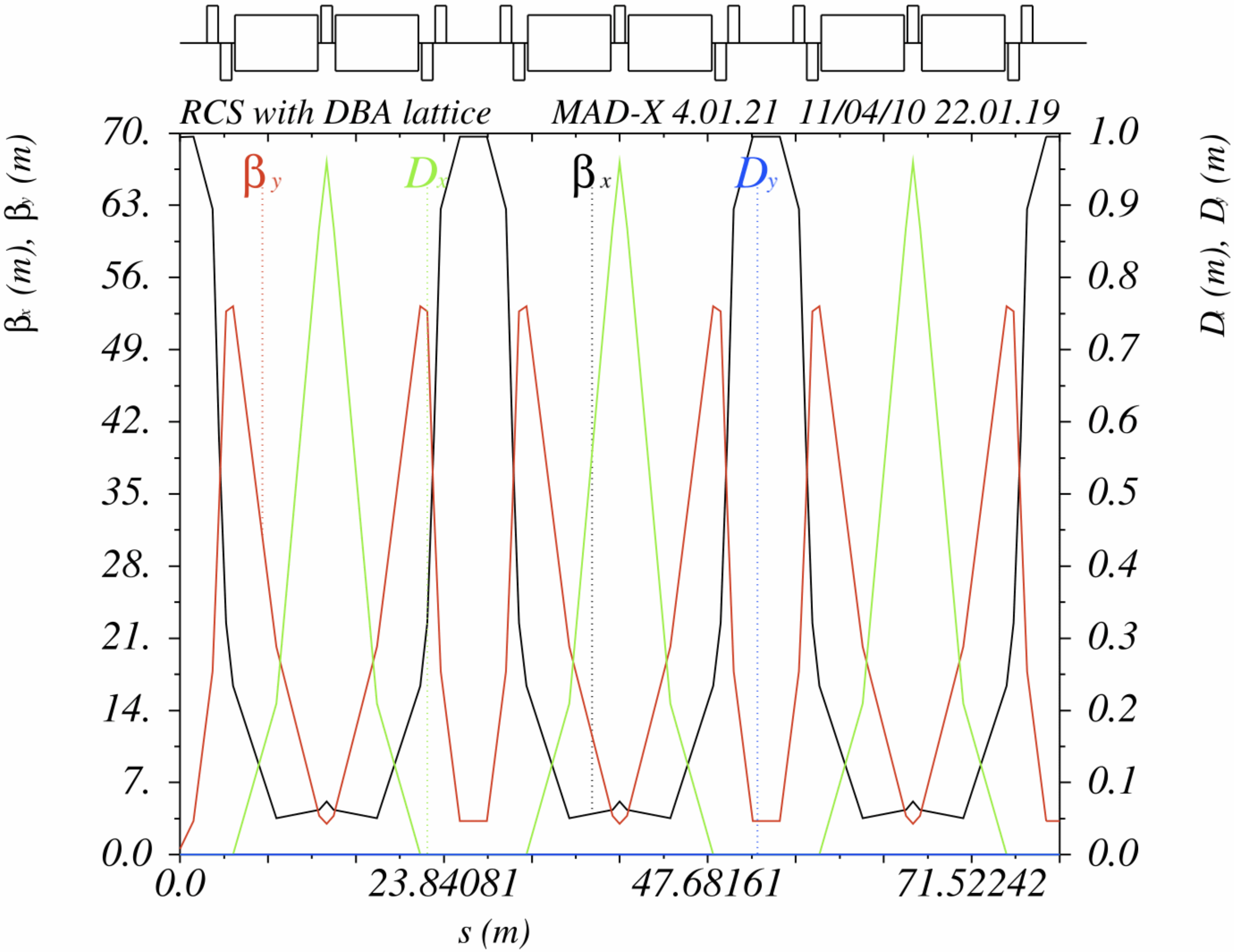


18 sided ring (20 deg per side)
15-16 used for RF cavities.
2 transfer lines.

Rough Orientation of New Booster and Transfer Lines



Lattice Using Double Bend Achromat with Doublets



Dx, and D'x are zero outside the dipoles.

Dipole length=7.5m means B-field at 8GeV=0.7T

Phase advance=254 deg/cell

Quads are 1m long. Max B' = 20 T/m @ 8GeV.

Long straights about 5 m in length.

Can optimize further, e.g. beta functions, use triplet double bend achromat etc.

Some MADX Lattice Notes

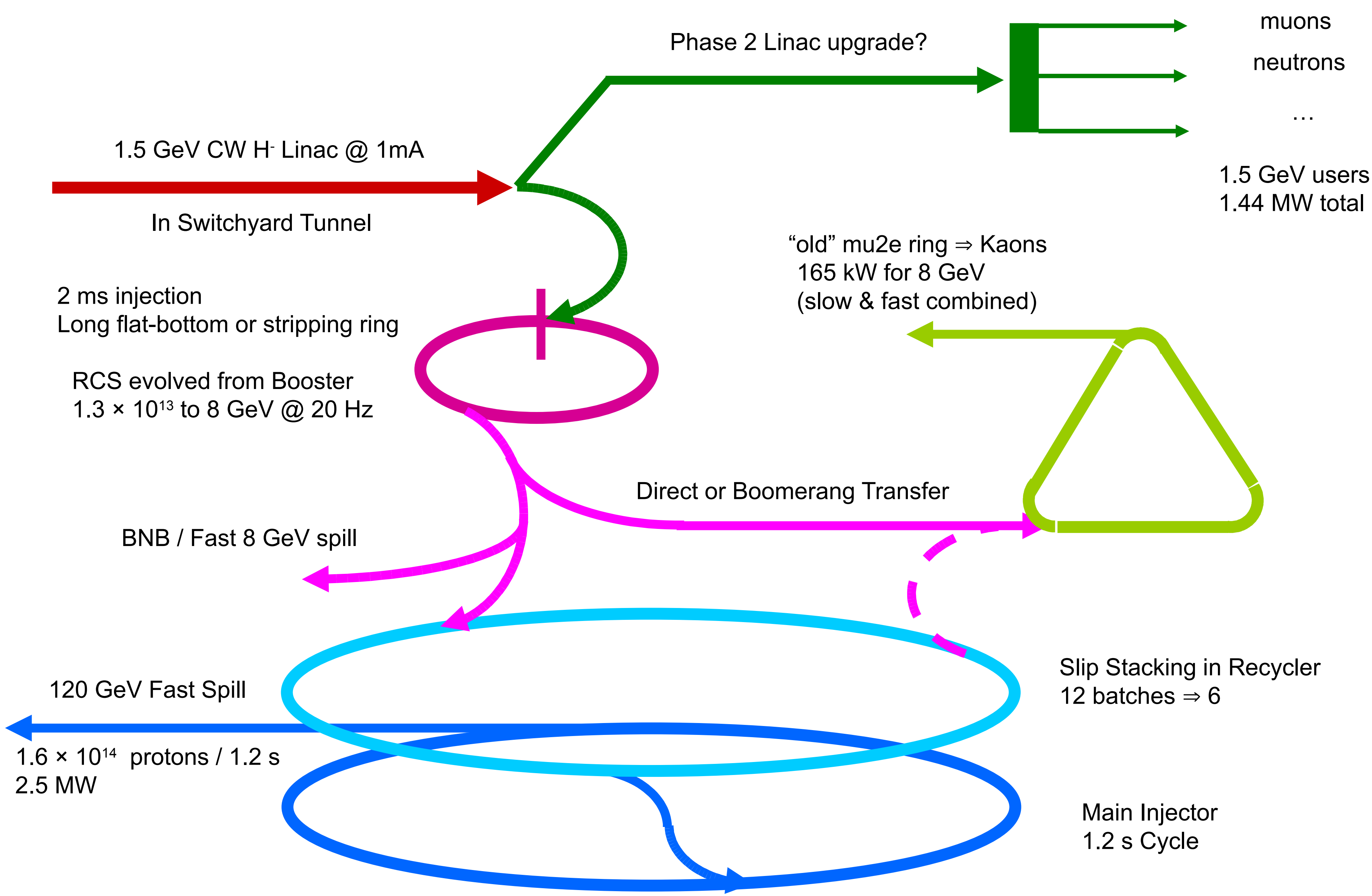
- Qx and Qy optimized to 12.7 units. (12.7 was chosen because a FODO lattice with Qx=12.7 will have a transition energy ~10GeV).
- β_x(max) is 2x and β_y(max) is 2.6x bigger than present Booster. (Present Booster β_x(max) = 33.7m and β_y(max) = 20.5m)
- Transition energy: 18.7 GeV > 8GeV
- Injection energy is 1.5GeV.
- If RF cavity takes up 3m of straight section space, 2m are left for sextupoles etc. (14-15 cavities)

```
@ NAME         %05s "TWISS"
@ TYPE         %05s "TWISS"
@ SEQUENCE     %03s "DBA"
@ PARTICLE     %06s "PROTON"
@ MASS         %le        0.938272013
@ CHARGE       %le                  1
@ ENERGY       %le                1.5
@ PC           %le        1.170318602
@ GAMMA        %le        1.598683515
@ KBUNCH       %le                  1
@ BCURRENT     %le                  0
@ SIGE         %le                  0
@ SIGT         %le                  0
@ NPART        %le                  0
@ EX           %le                  1
@ EY           %le                  1
@ ET           %le                  1
@ LENGTH       %le        476.8161183
@ ALFA         %le     0.002870480023
@ ORBIT5       %le                 -0
@ GAMMATR      %le          18.664774
@ Q1           %le               12.7
@ Q2           %le               12.7
@ DQ1          %le       -50.78657816
@ DQ2          %le       -69.16605339
@ DXMAX        %le       0.9597108956
@ DYMAX        %le                  0
@ XCOMAX       %le                  0
@ YCOMAX       %le                  0
@ BETXMAX      %le        69.71567821
@ BETYMAX      %le        54.81147905
@ XCORMS       %le                  0
@ YCORMS       %le                  0
@ DXRMS        %le       0.4480074709
@ DYRMS        %le                  0
@ DELTAP       %le                  0
@ SYNCH_1      %le                  0
@ SYNCH_2      %le                  0
@ SYNCH_3      %le                  0
@ SYNCH_4      %le                  0
@ SYNCH_5      %le                  0
@ TITLE        %20s "RCS with DBA lattice"
@ ORIGIN       %20s "MAD-X 4.01.21 Darwin"
@ DATE         %08s "11/04/10"
@ TIME         %08s "22.01.19"
```

The Injector Chain

- H- source
- RFQ
- Linac 1.5GeV fits in present enclosures
  - Pulsed or CW operation (can feed muon expt)
- Booster/RCS
  - Using present MI-8 line to inject into MI/RR.
- Slow spill (option)
  - Inject into Tev tunnel from MI using P1 line for slow spill.
  - Or spill from mu2e.
- Slip stacking in RR
  - Accept 12 Booster batches.
- MI 2MW beam for neutrino experiments.

PrX IC-α


Phase 2 Linac upgrade?
muons
neutrons
…
1.5 GeV users
1.44 MW total
1.5 GeV CW H- Linac @ 1mA
In Switchyard Tunnel
"old" mu2e ring ⇒ Kaons
165 kW for 8 GeV
(slow & fast combined)
2 ms injection
Long flat-bottom or stripping ring
RCS evolved from Booster
1.3 × 10^13 to 8 GeV @ 20 Hz
Direct or Boomerang Transfer
BNB / Fast 8 GeV spill
120 GeV Fast Spill
1.6 × 10^14 protons / 1.2 s
2.5 MW
Slip Stacking in Recycler
12 batches ⇒ 6
Main Injector
1.2 s Cycle

CW

- 1mA CW linac
- Injection into Booster/RCS for 2ms at 20Hz.
- Same frontend as ICD2
  - Rest of duty factor goes to 1.5GeV experiments.

RCS/Booster

- Injection energy is 1 GeV to 1.5GeV
- Ramp rate is 20 Hz
- Extra cycles (extractions to MI at 10Hz for 1.2 s cycle time, 1 s cycle time should be considered)
  - For 8 GeV experiments
- 1.3e13 protons per batch for 2MW MI beam

Conclusion

- This is a demonstration that the Booster, Switchyard, Transfer Hall enclosures and MI-8 line, along with existing utilities which can meet Project X requirements.
- Additional savings can be met by reusing elements and future upgrades.

Extra slides

Pulsed

- 20Hz linac (1.2 ms pulse length)
  - Same frontend as ICD1 except injection is at 1.5GeV
- Current is 20mA
  - <= 200 us to fill Booster
  - Remainder of 1.2ms pulse goes to 1.5GeV experiments

Increase in Beam Current

- By injecting at a higher energy, we can increase the beam current in the new Booster.
- Using the present maximum space charge tune shift at injection (400MeV) as starting point, we get the following increase injection beam intensity
  - Injection at 1GeV gives 2.5x increase
  - Injection at 1.5GeV gives 4.3x increase
- Efficiency must be increased
  - Reduced injection losses from chopping and higher energy
  - Larger aperture through RF
  - No notching losses – performed with chopper
  - No crossing transition

Pros/Cons compared to ICD1/2

- Less digging
- Use existing infrastructure like cryo CHL is right there, power, water etc.
- Booster components like correctors, septas, RF solid state drivers.

- MI test beam, switchyard is removed.
- Some decommissioning of Booster components.

Phase Relationships

	NOvA/LBNE	mu2e	Kaons	Other @ 1.5-3 GeV	Other @ 8 GeV
Phase 0	700 kW	0-30 kW	0	0	0-10 kW
IC-2v2 Phase 1	700 kW	400 kW	800 kW	800 kW	0-40 kW
IC-2v2 Phase 2	2.3 MW	400 kW	800 kW	800 kW	Large ?
IC-α Phase 1	2.5 MW	200 kW	150 kW	1.2 MW	15+ kW
IC-α Phase 2	2.5 MW	600 kW	1.2 MW	1.2 MW	165 kW

- Beam is extremely limited in Phase 0
  - Booster only has about enough capability for 700 kW NOvA/LBNE (w/o upgrades)
  - Every 10 kW for mu2e costs 150kW of neutrino

Assume IC-α Phase 2 is 3 GeV linac (ala IC-2v1) - for comparison

Max B-field for 1.5 GeV H - Ions

From J.P. Carneiro's paper (fnal_2740.pdf), the H- ion lifetime in its rest frame is given by 2 params, a and b.
For 1GeV H- ions, I will use the 800MeV data.

a and b here are the average of the two numbers in Table 1

```
a = (2.47 + 3.073) / 2 10^-14; (*s MV/cm *)
b = (44.94 + 44.14) / 2 ; (* MV/cm *)
```

Note : J.P.' s equation was a/e Exp[c/e]. Clearly c-> b. See "Handbook of Accelerator Physics and Engineering", pg 442.

```
τ0[e_] := a / e Exp[b / e]
```

The fraction lost per meter is given by

$$\lambda[e\_] := \frac{1}{c\,\beta\,\gamma\,\tau0[e]}$$

For 1.5 GeV H- ions, $\beta\,\gamma$ can be calculated as follows:

```
m0 = 938; (*MeV/c^2*)
ke = 1500; (*MeV*)

etot = m0 + ke;

γ = etot / m0 // N
2.59915
```

$$\text{Solve}\left[\gamma == \frac{1}{\sqrt{1-\beta^2}},\ \beta\right]$$

```
{{β → -0.923024}, {β → 0.923024}}

β = β /. %9[[2, 1]]
0.923024

c = 3 × 10^8; (*m/s*)
```

The momentum p of the H- ion at 1.5GeV is

```
p = Sqrt[etot^2 - m0^2] 10^-3 // N ; (*GeV/c*)

p
2.25033
```

A 1.5 GeV H- sees the following e-field for a B-field [T]

```
Ef[B_] := 3.197 p B
```

The Solution

I want to calculate the maximum B-field allowed for 0.1% loss of H-. It depends on the length of the curve! From Bill, the angle required is 180 degrees. This means that the distance covered by the 1.5GeV H- given the radius of curvature is

```
d[r_] := π r
```

r is given by the relationship between magnetic rigidity and momentum:
B r = 3.3357 p, with B in teslas, r in metres, p in GeV/c. Therefore

$$r[Bf\_] := \frac{3.3357}{Bf}\,p$$

The loss of H- must be <= 0.1% for the entire distance the H- travels in a magnetic field, i.e
d[r]*λ[e] <= 0.001
or
d[r[Bf]]*λ[Ef[Bf]] <= 0.001

Let's find the maximum B-field allowed

```
FindRoot[d[r[Bf]] λ[Ef[Bf]] == 0.001, {Bf, 0.1}]
{Bf → 0.270775}
```

i.e. Maximum Bfield is 0.4 T. This translates to a minimum radius of curvature of

```
r[Bf] /. %22[[1]]
27.722
```

i.e. 27m

For 0.1% loss of H- at 1.5GeV, require min. 27m radius bend

Space Charge Tune Shift

Only the coherent space charge tune shift is relevant for limiting the number of protons in the new Booster.
The scaling of this effect is from (4.86, page 151) of Ng which is $N / \beta\gamma^2$. If I believe that the maximum space charge tune shift of Booster is 0.4 (Table 4.2, page 157 of Ng) for injection at 400MeV, I can see how much more protons I can inject at 1GeV and 1.5 GeV.

First, I have to calculate β and γ at 400 MeV , 1 GeV and 1.5 GeV

```
In[1]:= m0 = 938 × 10^6; (*eV*)

In[2]:= k400 = 400 × 10^6; (*eV*)
        k1000 = 1 × 10^9; (*eV*)
        k1500 = 1.5 × 10^9; (*eV*)
```

Calculate the γ and β for each energy

- **400 MeV**

```
In[6]:= Solve[γ m0 == m0 + k400, γ] // N
Out[6]= {{γ → 1.42644}}

In[7]:= γ400 = γ /. First[%6]
Out[7]= 1.42644

In[8]:= Solve[1/Sqrt[1 - β^2] == γ400, β]
Out[8]= {{β → -0.713116}, {β → 0.713116}}

In[9]:= β400 = β /. Last[%8]
Out[9]= 0.713116
```

- **1000 MeV**

```
In[10]:= Solve[γ m0 == m0 + k1000, γ] // N
Out[10]= {{γ → 2.0661}}

In[11]:= γ1000 = γ /. First[%10]
Out[11]= 2.0661

In[12]:= Solve[1/Sqrt[1 - β^2] == γ1000, β]
Out[12]= {{β → -0.875066}, {β → 0.875066}}

In[13]:= β1000 = β /. Last[%12]
Out[13]= 0.875066
```

- **1500 MeV**

```
In[14]:= Solve[γ m0 == m0 + k1500, γ] // N
Out[14]= {{γ → 2.59915}}

In[15]:= γ1500 = γ /. First[%14]
Out[15]= 2.59915

In[16]:= Solve[1/Sqrt[1 - β^2] == γ1500, β]
Out[16]= {{β → -0.923024}, {β → 0.923024}}

In[17]:= β1500 = β /. Last[%16]
Out[17]= 0.923024
```

sc

Scaling

The scaling is
$\Delta\nu$ propto $N / \beta\gamma^2$ and so

$$\frac{\Delta\nu e}{\Delta\nu 400} = \frac{Ne}{N400} \frac{\beta 400\, \gamma 400^2}{\beta e\, \gamma e^2} = f \frac{\beta 400\, \gamma 400^2}{\beta e\, \gamma e^2}$$

where f is the factor which decribes the increase in beam current when $\Delta\nu e / \Delta\nu 400 = 1$. Therefore,

$$f = \frac{\beta e\, \gamma e^2}{\beta 400\, \gamma 400^2}$$

- **Increase in beam current for 1 GeV**

```
In[18]:= f1000 = β1000 γ1000^2 / (β400 γ400^2)
Out[18]= 2.5744
```

- **Increase in beam current for 1.5 GeV**

```
In[19]:= f1500 = β1500 γ1500^2 / (β400 γ400^2)
Out[19]= 4.29743
```

100%

100%

Heating by Eddy Current

- Formula for power loss per unit length (W/m) is
  - $$\frac{dP}{ds} = \pi^3 f_{\text{ramp}}^2 (B_{\max} - B_{\min})^2 r^3 d / \rho$$
    - Formula is from Chao and Tigner "Handbook of Accelerator Physics and Engineering", page 436.
  - For stainless steel pipe of thickness *d*=0.7mm and radius *r*=2 cm, ρ=1/(1.4 x 106) Ωm, f_{ramp} = 15Hz
- For 1 GeV injection, 8GeV extraction, loss is 6W/m.
- For 1.5GeV injection, 8GeV extraction, loss is 5W/m

RF Power

- Average RF power to beam at 1GeV injection energy: 440kW
- Average RF power to beam at 1.5GeV injection energy: 400kW

RF Power

Number of protons for Project X

In[1]:= $n = 2.6\times10^{13};$

Energy ramps from 1 GeV to 8 GeV or 1.5 GeV to 8GeV.
For the 1GeV case

In[2]:= $\Delta E1 = 8\times10^{9} - 1\times10^{9};$ (*eV*)

For the 1.5 GeV case

In[3]:= $\Delta E15 = 8\times10^{9} - 1.5\times10^{9};$ (*eV*)

Frequency of injection and ramp

In[4]:= framp = 15; (*Hz*)

Charge of electron

In[5]:= $q = 1.6\times10^{-19};$ (*C*)

Average RF power to beam for 1 GeV injection

In[6]:= P1 = n ΔE1 q framp

Out[6]= 436800.

or 440 kW

Average RF power to beam for 1.5 GeV injection

In[7]:= P15 = n ΔE15 q framp

Out[7]= 405600.

or 400 kW

Peak Power

Peak RF power to beam occurs at 8GeV and flattop time is ?? us

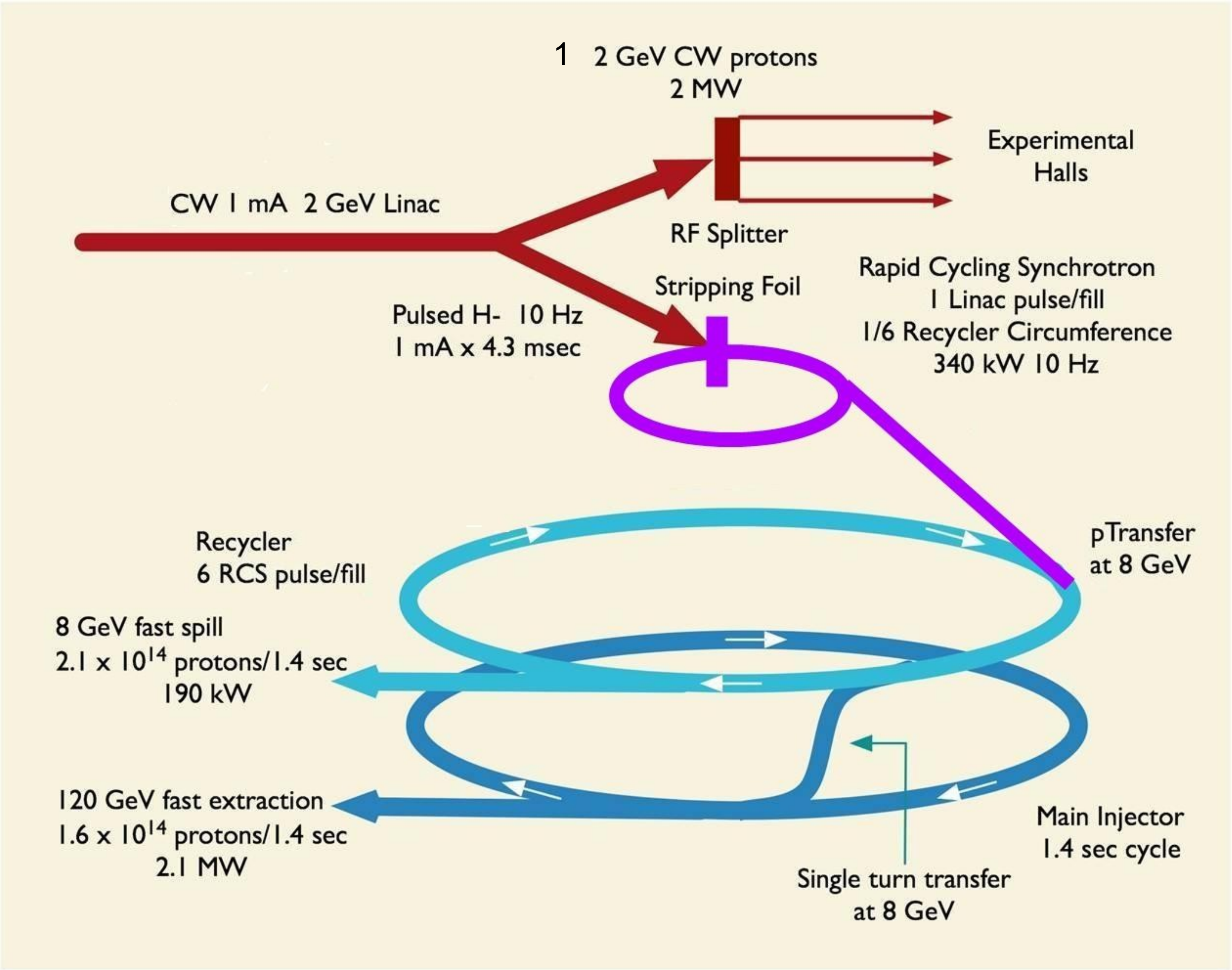
100%

MADX Input File

```
// Using a Double Bend Achromat lattice for an RCS which fits in Booster
TITLE "RCS with DBA lattice";
Option, -echo,-info,warn;

Ncells=18;             // number of DBA straight sections
cspeed=2.99792458e8;   // (m/s) speed of light
fRF=52.814e6;          // (Hz) RF frequency at flattop
//harmonicN=85;        // harmonic number. ******** Note: NOT 84 ********
harmonicN=84;          // harmonic number.
pathLen=cspeed/(fRF)*harmonicN;// Total path length per turn
Lcell=pathLen/Ncells;  // (m) length of DBA cell

value, Ncells, Lcell, pathLen;

/*
   quad coeficients are calculated from the focal lengths
   and length of quads.
   These values come from rcs.nb

   The basic RCS cell is:

   {o1 Qf(qfK) o[L2] Qd(qdK) o[L3] } DBA {o[L3] Qd(qdK) o[L2]  Qf(qfK) o1}

   with DBA:
   {B(Lb, theta), o(Ldrift), Qf(KDBA), o(Ldrift), B(Lb, theta)}

*/

L2 = 0.2;               // (m)
L3 = 0.3;               // (m)
Lb = 7.5;               // (m)
Ldrift = 0.3;           // (m)

KDBA = 0.473088;        // (m^-2)
qfK  = 0.421519;        // (m^-2)
qdK = -0.544458;        // (m^-2)
Lquad = 1.00;           // (m) length of all the quads
Lqdba = 1.0;
bAngle = 10*pi/180.;    // (rad) bend angle of each dipole is 10 degrees.
                        // because RCS cell bends by 20 degs and there are two dipoles.

// the components in the RCS

// The doublets
QF1: QUADRUPOLE, L=Lquad, K1=qfK;
DL2: DRIFT, L=L2;
QD1: QUADRUPOLE, L=Lquad, K1=qdK;
DL3: DRIFT,L=L3;

// The DBA
B1: SBEND, L=Lb, ANGLE=bAngle;
Ddrift: DRIFT, L=Ldrift;
QDBA: QUADRUPOLE, L=Lqdba, K1=KDBA;
D2: DRIFT, L=Ldrift;
B2: SBEND, L=Lb, ANGLE=bAngle;


O1: DRIFT, L=(Lcell-Lqdba-4*Lquad-2*Lb-2*(L3+L2+Ldrift))/2.0;

value, (Lcell-Lqdba-4*Lquad-2*Lb-2*(L3+L2+Ldrift))/2.0;
```

```
// define the DBA first

dbaCell: line=(O1,
               QF1, DL2, QD1, // doublet
               DL3,
               B1, Ddrift, QDBA, Ddrift, B2,
               DL3,
               QD1, DL2, QF1, // doublet
               O1);
dba: line=(18*dbaCell);

// define the beam for the RCS
beam, particle=proton, sequence=dba, energy=1.5;

use, period=dba;

match, sequence=dba;
/***** for doublet optimization *********/

vary, name=qf1->K1, step=0.00001;
vary, name=qd1->K1, step=0.00001;
global, sequence=dba, Q1=12.7;
global sequence=dba, Q2=12.7;
lmdif, calls=100, tolerance=1e-21;
endmatch;


/***** for zero dispersion optimization ********/
/*
        Don't forget to set
              dba: line=(dbaCell)
        i.e. remove Ncells in the above line.
*/
/*
vary, name=qdba->K1, step=0.00001;
constraint, sequence=dba, RANGE=#e, DX=0;
lmdif, calls=100, tolerance=1e-21;
endmatch;
*/



// define the type and amount of output for TWISS
select, flag=twiss, column=name,s,x,y,mux,betx,bety,dx,dy;

// calculate the Twiss prameters
// twiss, save, centre, betx=.1, bety=.1, file=twiss.out;
twiss, save, centre, file=twiss.out;


plot,haxis=s,hmin=0.,hmax=3*Lcell,spline,vaxis1=betx,
        bety,vaxis2=dx,dy,colour=100;

//twiss,deltap=-0.0001:0.0001:0.00005;

//plot,table=summ,haxis=deltap,vaxis=q1,q2;

stop;
```

ICD2


1 2 GeV CW protons
2 MW
Experimental
Halls
CW 1 mA 2 GeV Linac
RF Splitter
Rapid Cycling Synchrotron
1 Linac pulse/fill
1/6 Recycler Circumference
340 kW 10 Hz
Stripping Foil
Pulsed H- 10 Hz
1 mA x 4.3 msec
Recycler
6 RCS pulse/fill
pTransfer
at 8 GeV
8 GeV fast spill
2.1 x 10^14 protons/1.4 sec
190 kW
120 GeV fast extraction
1.6 x 10^14 protons/1.4 sec
2.1 MW
Main Injector
1.4 sec cycle
Single turn transfer
at 8 GeV