Folded Waveguide Research

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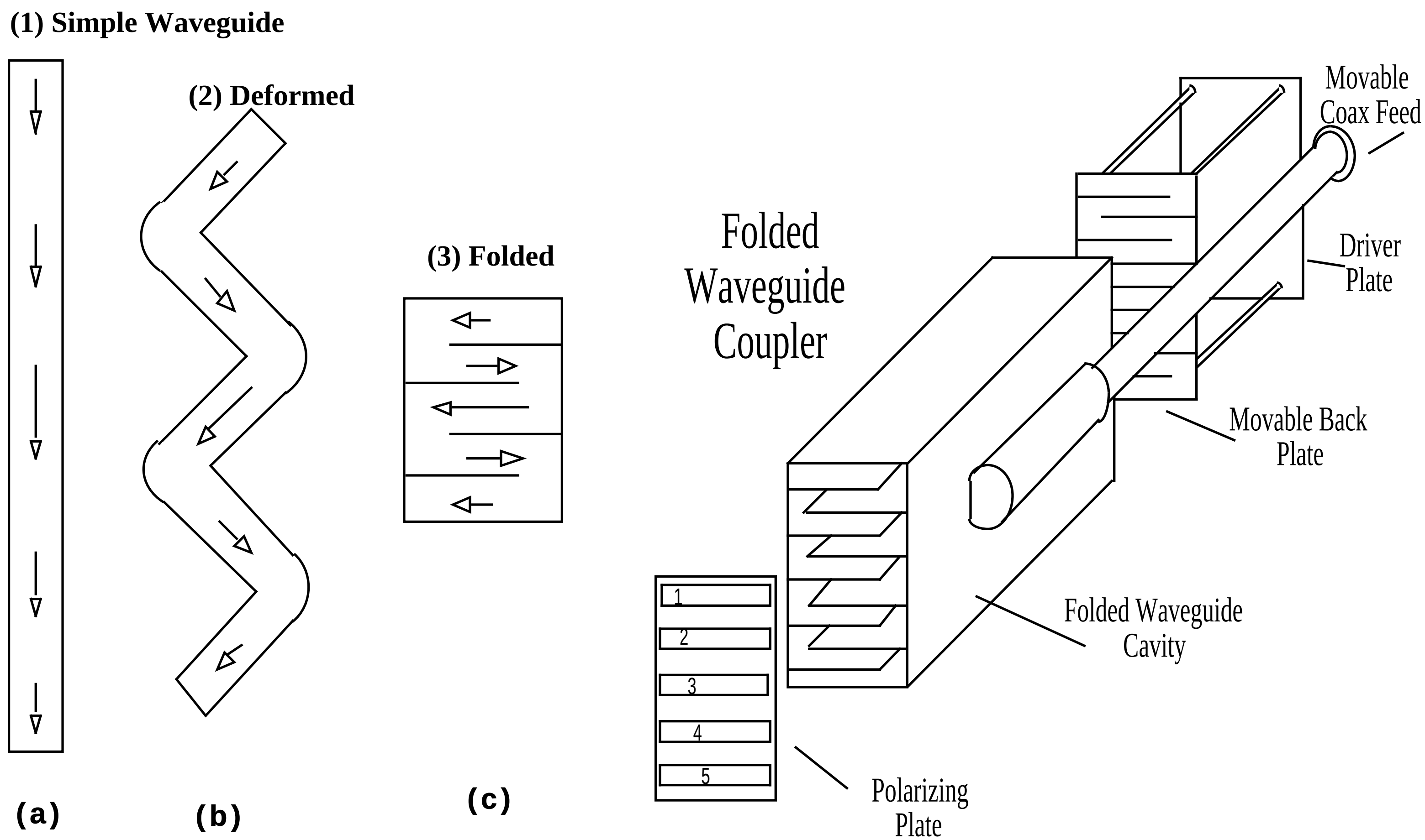
Outline

- Motivation for the Folded Waveguide and concept description
- History, present status
- Early modeling and measurements
- Alternative design possibilities
  - Monopole and dipole configurations
  - Half-wavelength and quarter-wavelength options
  - Wire faceplate
- Designs for particular machines
  - PBX/TFTR, DIII-D, ITER, FTU
- Experimental test of the folded waveguide concept on ET

Folded Waveguide and Waveguide ICRF launchers

- Motivation
  - Achieve high power density > 2 kW/cm^2
  - Compact size
  - Polarization and launch spectrum flexibility
  - Low Electric fields near the plasma
  - All metal, rigid structure
  - Internally matched
  - Low mutual coupling in arrays
- Applications
  - Small devices and small port size devices
  - Reactors
  - Current drive arrays

The Folded Waveguide Concept



FWG offers many advantages

- High power and high power density
- Low internal electric fields near the plasma
- No Faraday shield
- Good mechanical strength
- Ceramics only in well-shielded feed line
- Internally matched
- Excellent array properties
- High Q, high efficiency

FWG inconveniences are minimal

- Narrowband device requires cavity mechanical tuning:
  – higher mode operation provides additional frequencies
- Large device for lower frequency: use λ/4 configuration
- Unproven on tokamak
  – ORNL low & high power tests quite successful
  – New PBX/TFTR program for tokamak demonstration
- Ripple in antenna pattern dies out rapidly away from face plate- doesn’t appear to be a problem

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Folded Waveguide Development History

- Extensive hardware development
  - Recent low and high power tests
  - Previous hardware tests
  - Electromagnetic modeling- ARGUS and EMAS
  - Thermal modeling
  - Disruption force modeling

- Successful Development FWG unit
  - 1/2 & 1/4 wavelength configurations

- TFTR/DIIID/PBX unit completed and available for testing
  - High power tests complete and largely successful
    - Achieved > 500 kW on RFTF for 1 sec pulses with two face plate versions
  - Looking for new suitable tokamak or stellarator for POP tests

Status of FWG Development

- Several configurations studied
- Operation with high E and B fields into low density RFTF plasma
- Low power tests
  - pattern measurements: similar to loop antenna away from surface
  - matching, Q characterization: well predicted by simple theory
- Loading & power coupling calculations
- Advanced mechanical & disruption calculations

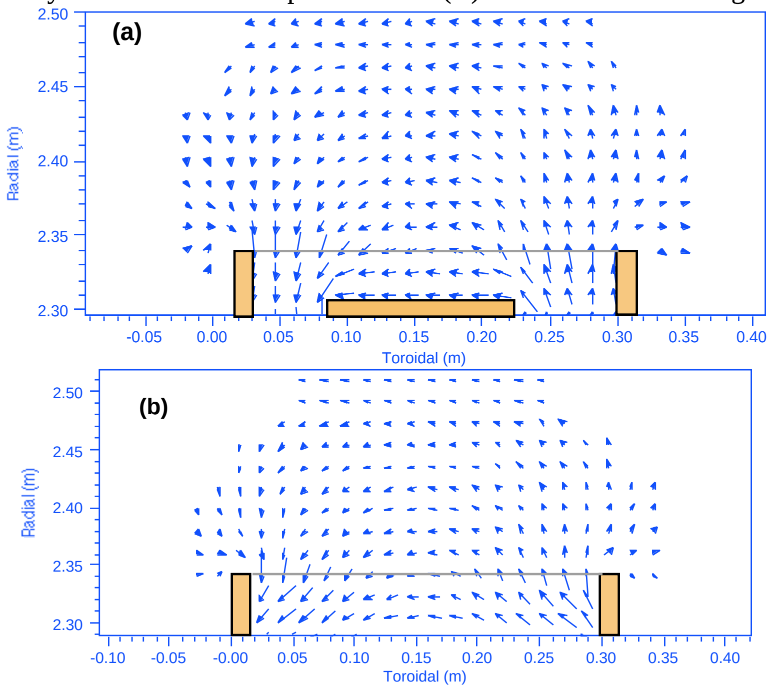
FWG Modeling

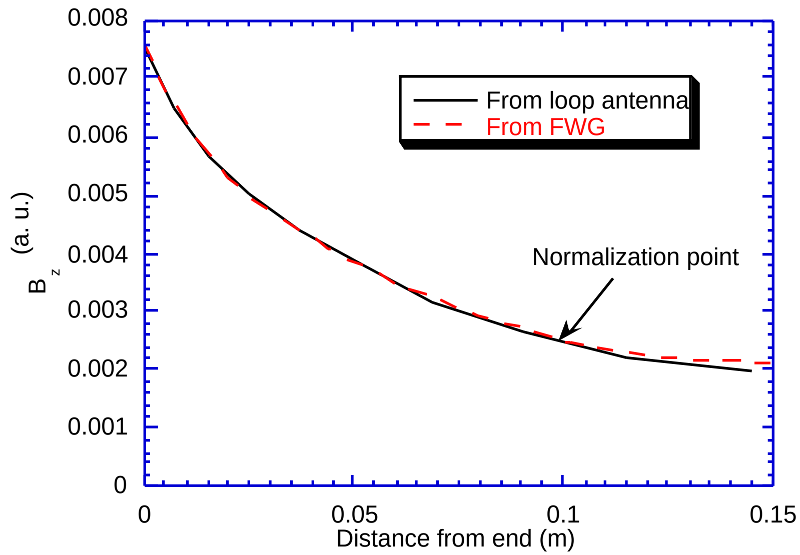
- Cavity model for basic parameters
  - F_o , Q, E_{max} , B_{max}
- Network model to describe coupling and matching circuits
- 2D finite difference code for accurate vane-tip E-field enhancement calculation
- 3 D codes ARGUS, EMAS for field & current calculations everywhere

Fields outside FWG

Outside a FWG, the magnetic field profile is very similar to that of a strap antenna with similar outside dimensions.

ARGUS simulation of FWG for TFTR/PBX and strap antenna with same geometry. Field from loop antenna (a) and folded waveguide (b)

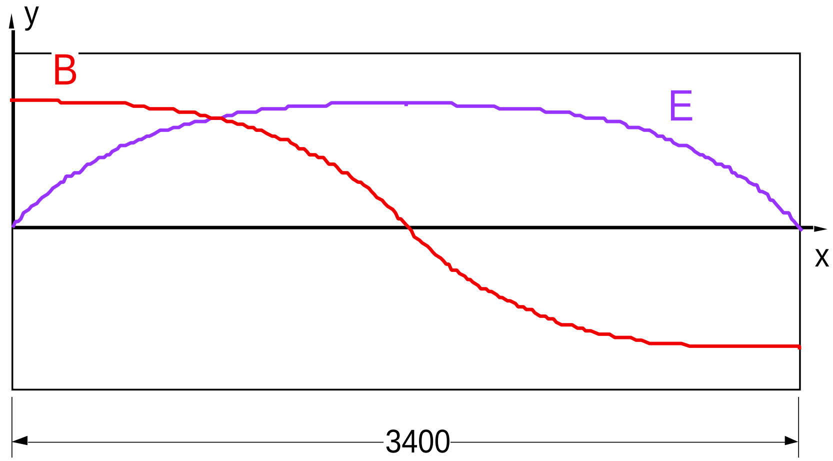




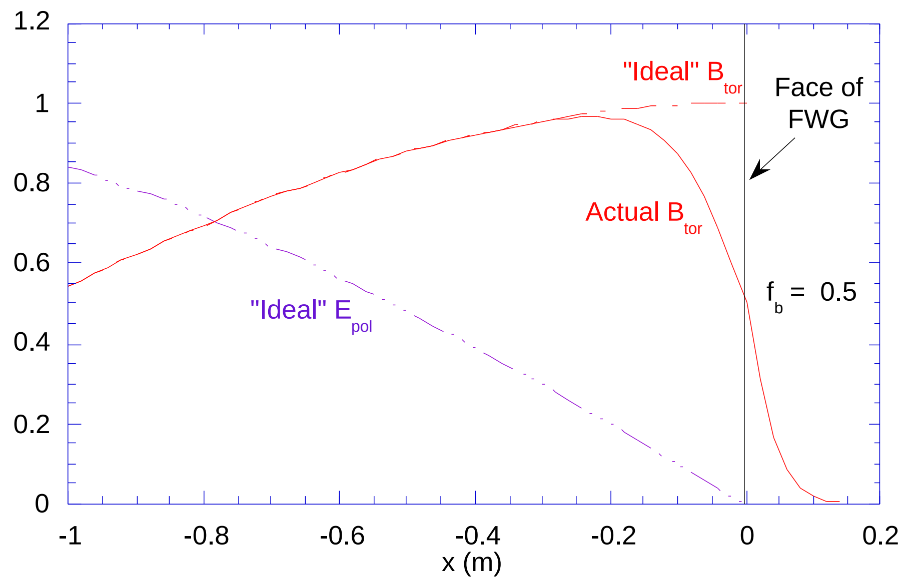
Fields inside FWG

For closed waveguide resonant cavity, simple relation between max electric field (in center) and max magnetic field (at ends)

$$B_{ideal} = \frac{\mu_o \pi}{377\ k_o\ L_x} E_{ideal}$$



FWG field at radiating end departs from ideal



Power Limitation

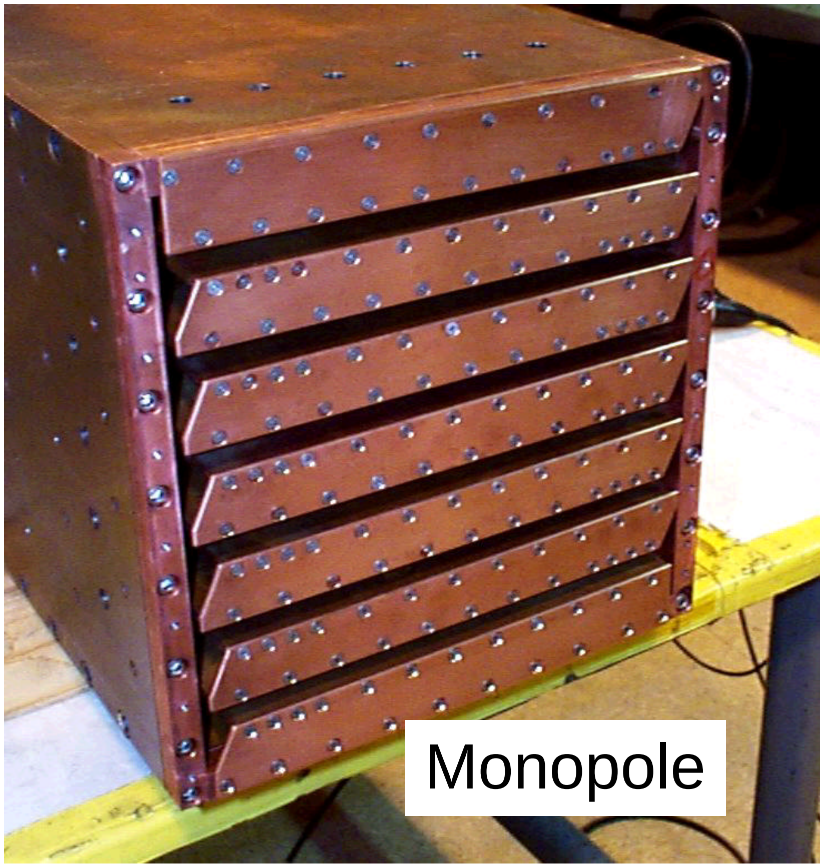
- Want maximum B_{rf} at plasma with minimum E_{rf}
  - FWG has low wave impedance at plasma edge
- Electric field breakdown
  - Achieved 44 kV/cm in development tests
  - Electric field enhancement at vane tips ~2:1 (can be reduced with larger vanes)
- High current at joints
  - 50A/cm along vane & face plate joints

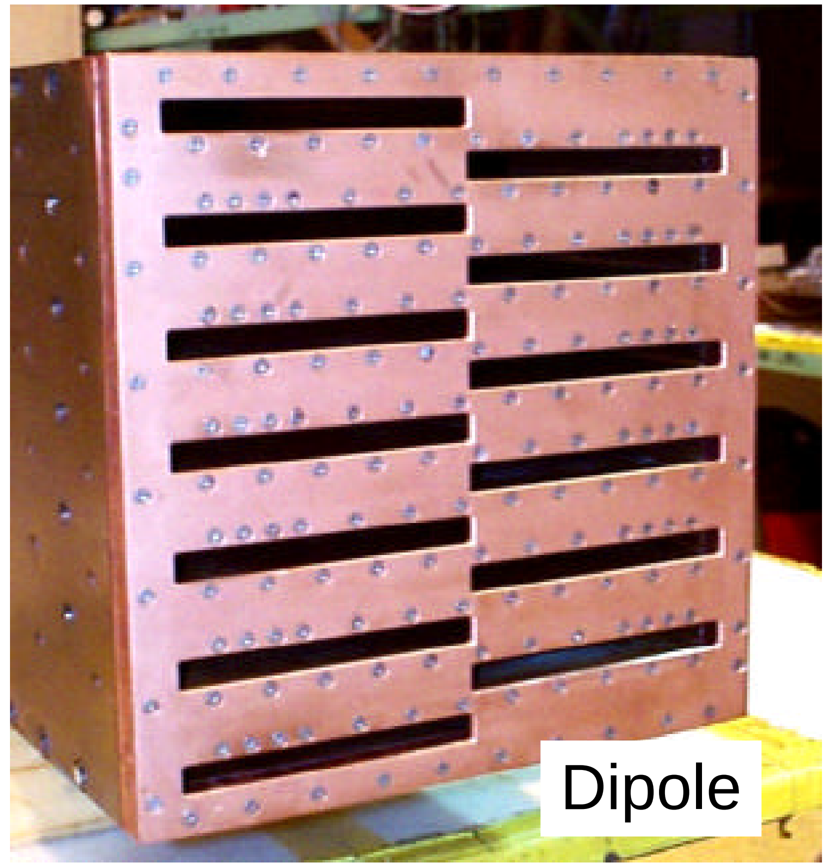
FWG Loading Calculations

- Rant-3D antenna loading code modified to handle FWG
- Assumes equivalent face-plate current & B field profile
- Peak aperture B_{rf} based on cavity model with E_{max}
- Monopole and dipole models
- Calculates power dissipated in plasma
- Calculates launch spectrum in plasma

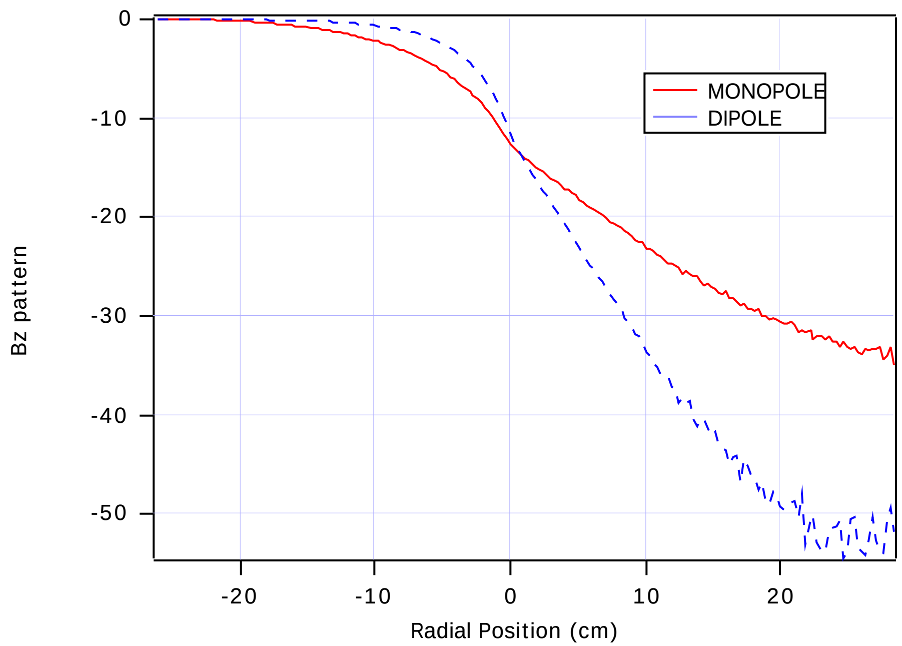
Monopole and Dipole Face Plates

Two RFTF test configurations shown without bumpers





Field measurements on monopole and dipole face plates



Radial field variation

Loading and efficiency measurements

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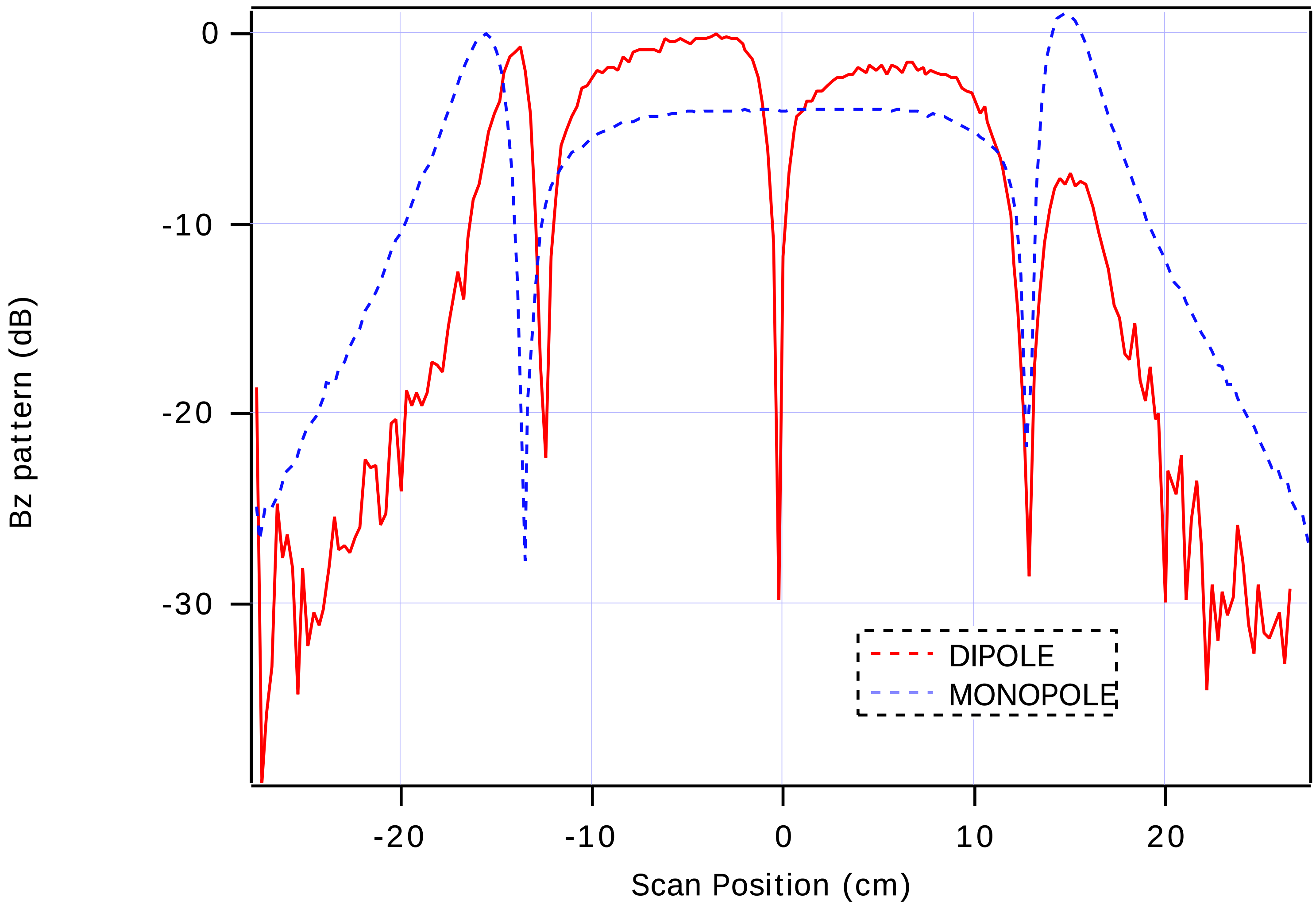
“Toroidal” Bz pattern measurements

5 mm spacing



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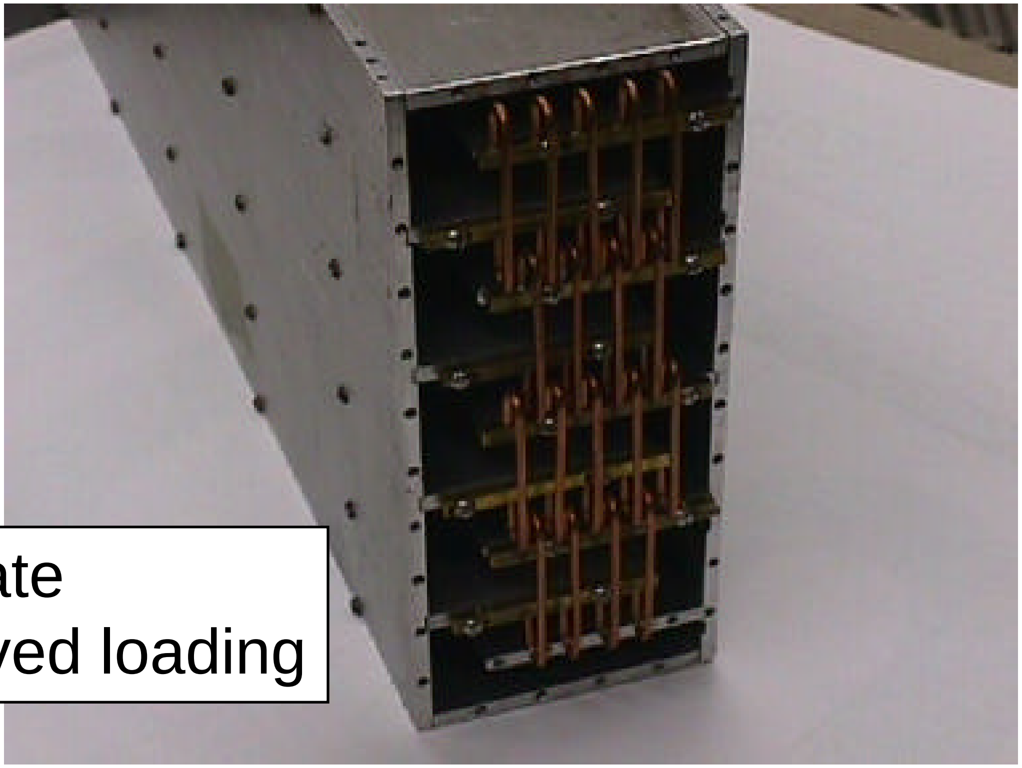
Quarter-wavelength configuration

- Shorter length version ~ half the $\lambda_g/2$ length
- Open circuit at back end, plasma end identical to half wavelength
- Improved feed options
  - rear feed
  - sidewall feed
- Demonstrated at high power, no load

Improved face plate designs

•Improve coupling
•Options for launch spectrum
•Improve disruption strength



Wire face plate
Gives improved loading

Many interesting waveguide configurations

- Folded waveguide- several variations
- Stacked stripline
  - Used at U. Wisc.
- Folded stripline
  - Small development unit
- Ridged waveguide- open end
  - Good candidate for reactor for ICRF heating
- Ridged or rectangular waveguide with shorting strap launcher
  - Considered for NCSX at 350 MHz
- Folded waveguide feeding loops for CD
- Single super-power klystron and ridged waveguide transmission capable of >20 MW per unit

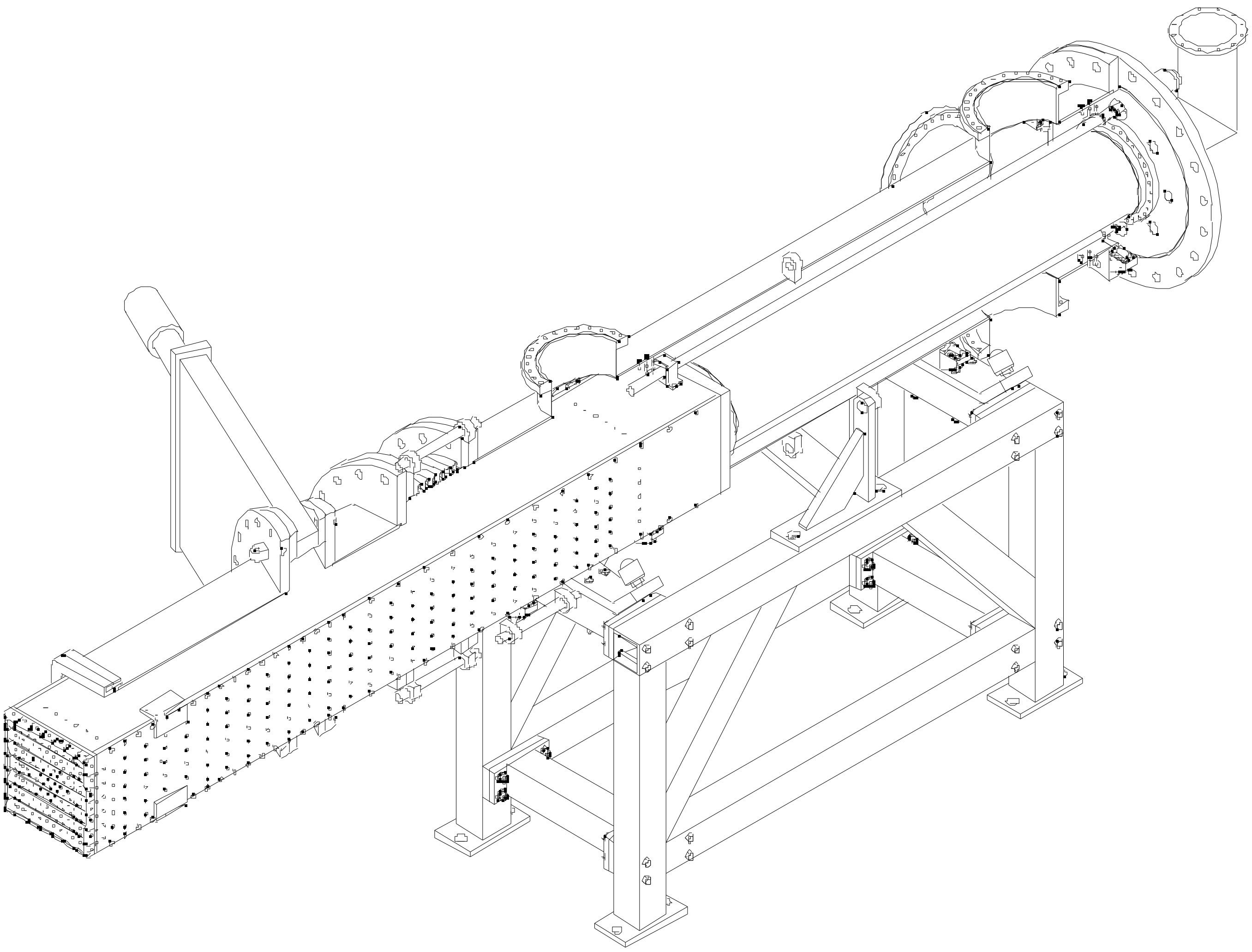
Potential FWG testing sites

- DIII-D
  - TFTR unit available and could be used for heating
  - Current drive array looks feasible
- CMOD
  - High power density allows room for proposed LHCD launcher by combining 2 ICRF heating antennas
- Electric Tokamak (ET) at UCLA
  - Port available
  - 80 MHz transmitter available
- NSTX- HHFW/IBW possibilities
- Tore-Supra
  - Long pulse capability of interest
  - Prototype completed
- Textor
  - Significant interest
  - 38 MHz version required to match available power

PBX/TFTR design

- 57 MHz, 2-4 MW design
- Rotatable, square cross section for Fast wave or Ion-Bernstein Wave launch
- 12 vanes; 0.314 x 0.314 m OD
- Quarter wavelength, rear wall feed
- Retractable design with vacuum lock
- Plated SST walls with bolt on vanes

TFTR/DIIID/PBX/ET/TEXTOR FWG



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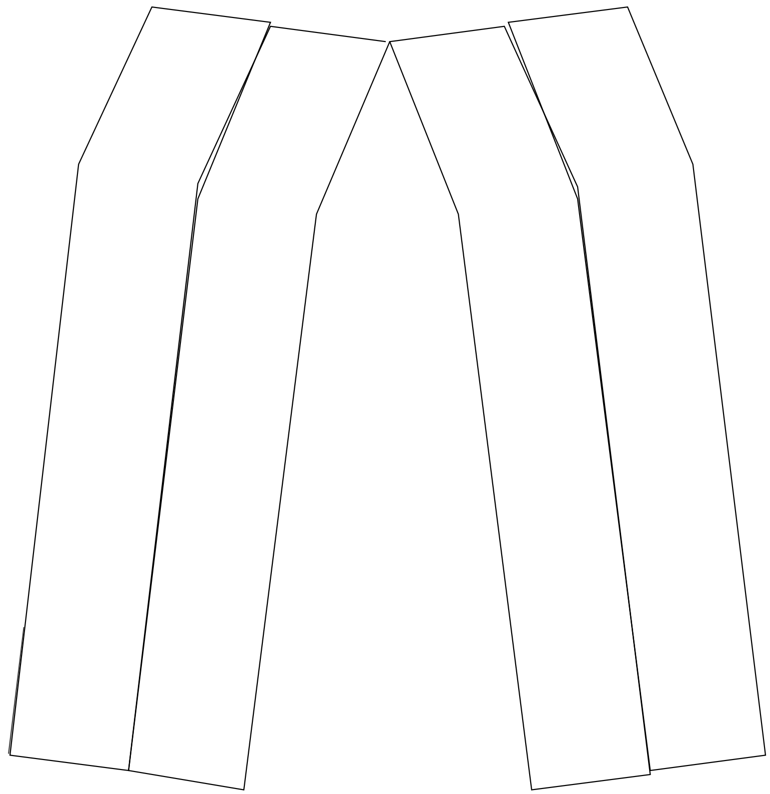
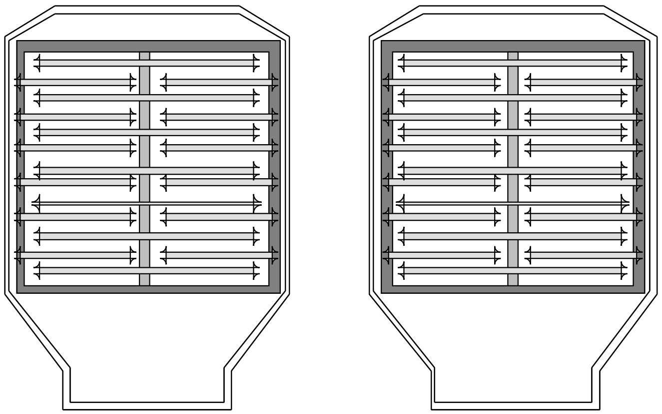
>4MW 120 MHz FWG FWCD array feasible for DIII-D



Top view



Front View

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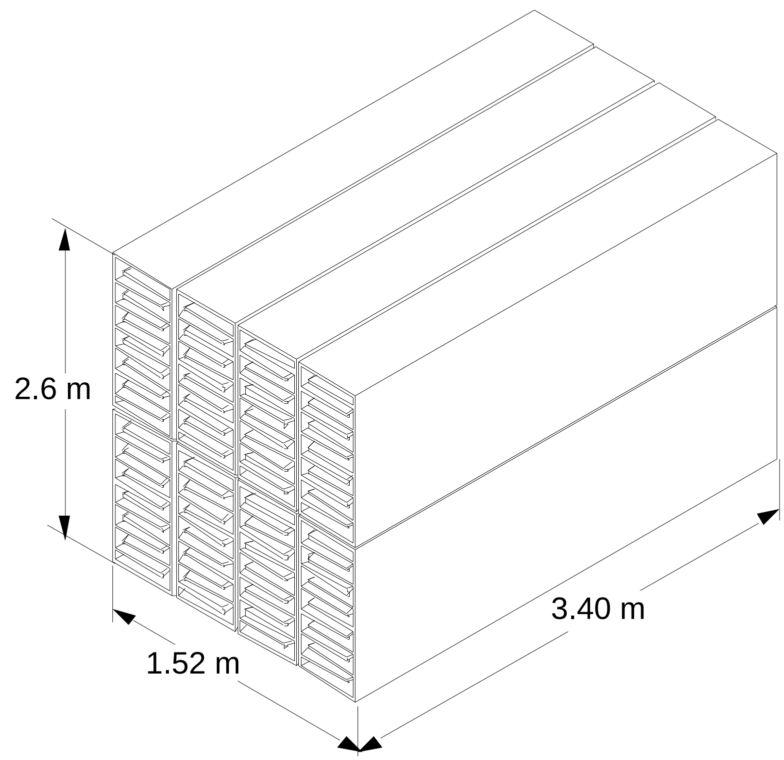
The FWG is ideal for ITER

- Satisfies design goals:
  - In-port launcher configuration
  - High power density
  - Large plasma-antenna separation
  - Frequency tuning not required(?)
  - Launch spectrum flexibility
  - High speed matching

ITER 1996 FWG design
60 MHz



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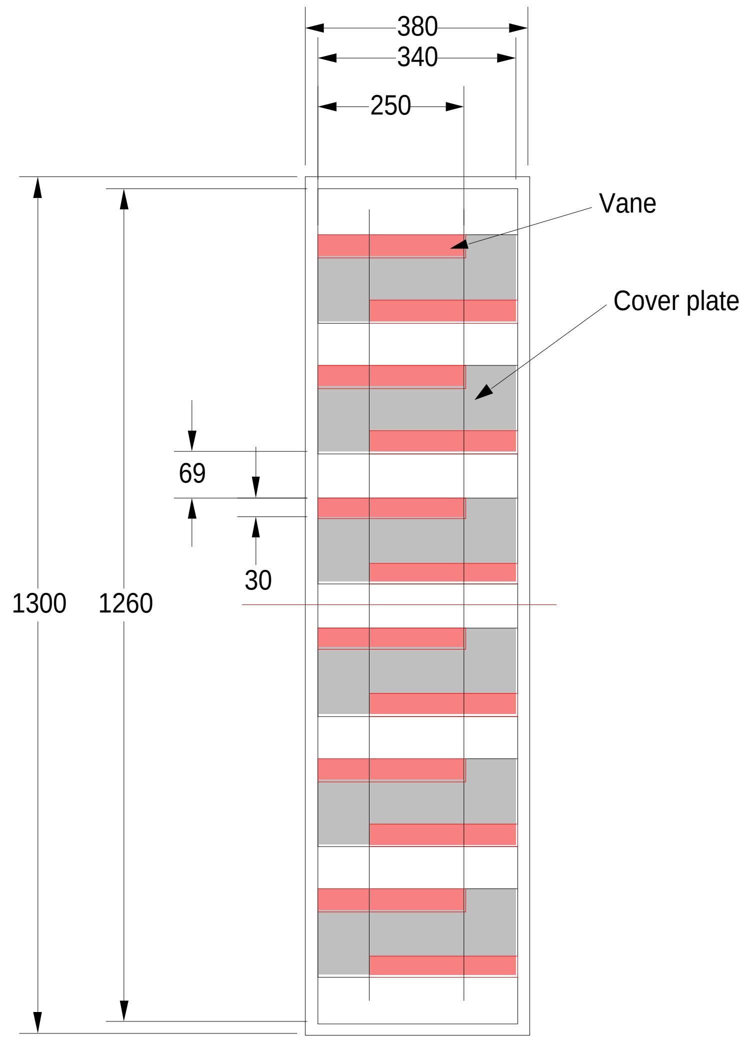
ITER FWG details

- 12 vanes
- 6.9 cm gap between vanes
- 3 cm thick vanes
- length of l/2 guide is 3.4 m (@ 60 MHz)



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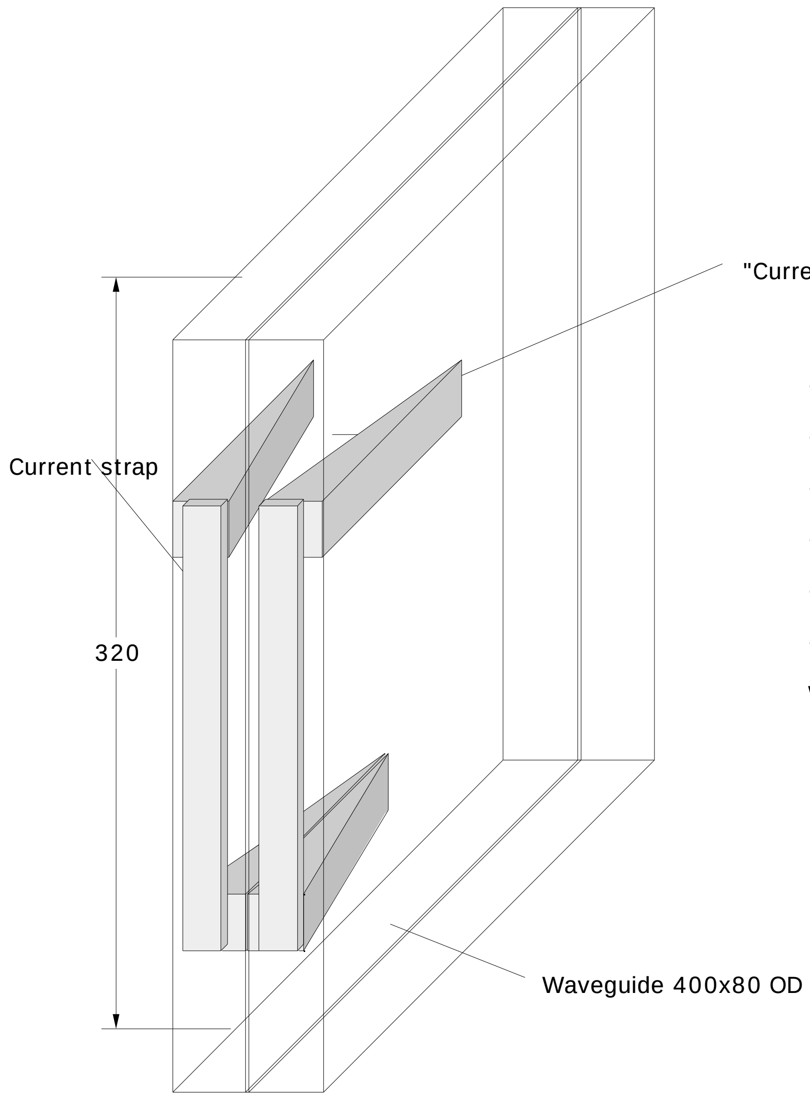
ITER FWG Array design

- 2 x 4 element array
- 55-60 MHz nominal frequency
- Rear-wall feed
- Predict 32 MW 0-π phasing; 58 MW 0- π/2 with Rant3D (using simple field approx.)
- Similar value for 0-π reported by Heikkinen at ITER design meeting (May 96)

FTU / IGNITOR/NCSX? Waveguide FW launcher



- Dual 400 MHz waveguide input
- Fits high field tokamak ports
- High power sources available
- Waveguide to Current strap conversion
- Adjustable launch spectrum
- HHFW launch on NCSX proposed with compact 350 MHz unit

TSB, DWS

Experimental plans

- Collaboration with Bob Taylor on ET experiment at UCLA
  - Large ports
  - Flexible geometry configuration
  - Good access for testing folded waveguide
- Install and test the PBX/TFTR folded waveguide (57 MHz) and/or the development waveguide (80 MHz) for power limit/voltage testing in presence of plasma
- Near-term use relatively low-power (≈ 20 kW source)
- Longer-term, modify FMIT 80 MHz unit at UCLA for high-power (~ 1 MW) tests with plasma